GEOPHYSICAL SURVEYS FOR ASSISTING IN DETERMINING THE GROUNDWATER RESOURCES PUU O HOKU RANCH SITE ISLAND OF MOLOKAI, HAWAII

Blackhawk Geometrics Project Number 9912POH

Prepared For:
PUU O HOKU RANCH, LTD.

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1.0 INTRODUCTION

This report contains the procedures and results of surface geophysical surveys conducted to assist in determining the groundwater resources on property owned by Puu o Hoku Ranch, Ltd., Island of Molokai, Hawaii. The geophysical method employed during this survey was Time-Domain Electromagnetic (TDEM) soundings. The surveys were performed by Blackhawk Geometrics (Blackhawk) for Puu o Hoku Ranch, Ltd. during December 5 to December 8, 1998. Survey oversite was provided by Tom Nance of Tom Nance Water Resource Engineering (TNWRE). The TDEM soundings for this survey were positioned on the ranch property above and below the main water tank, and on pasture land located below the ranch buildings as shown on Figure 1-1.

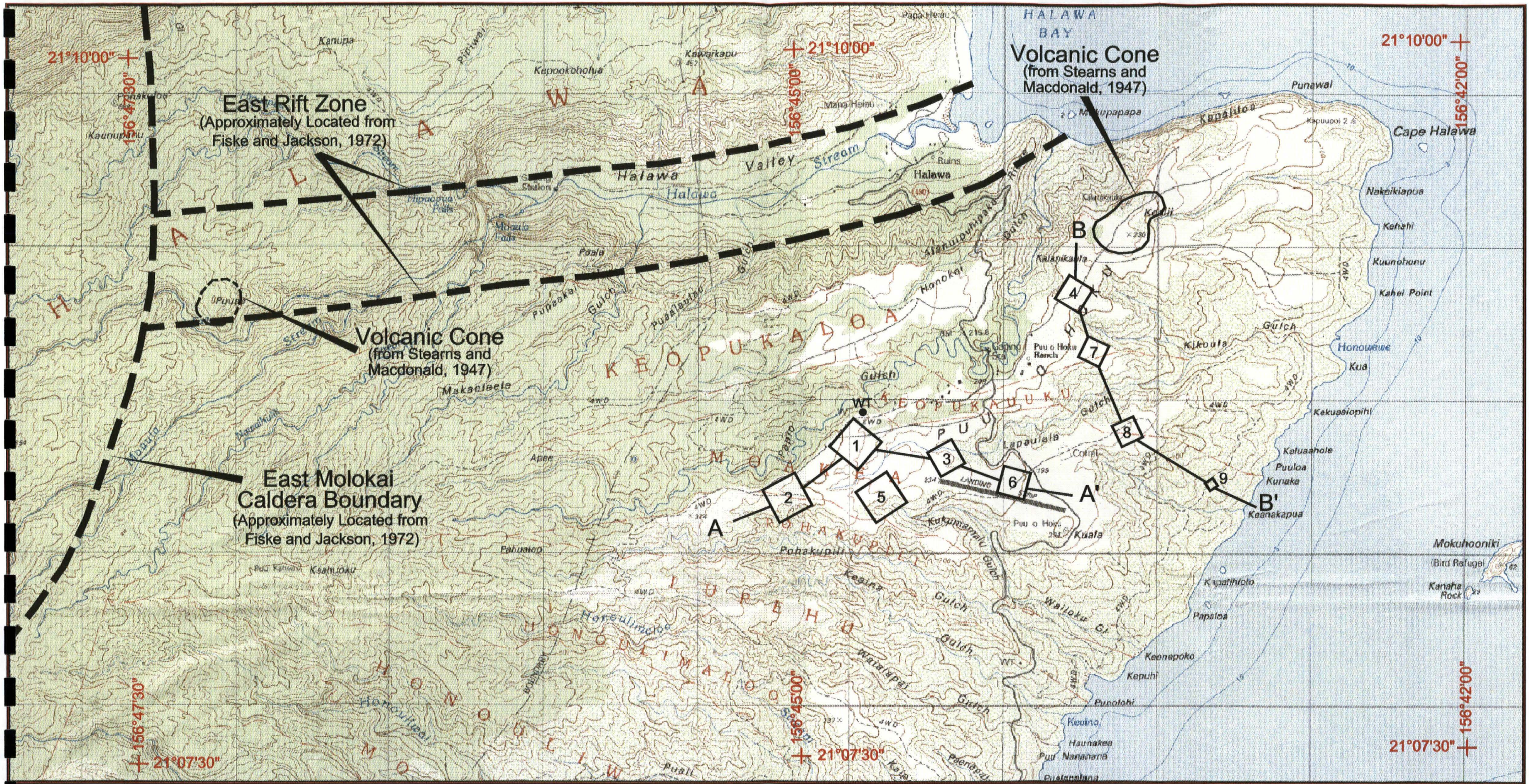
The Puu o Hoku Ranch of Molokai is located on the eastern portion of the island. The ranch property lies on the eastern dipping flank of the East Molokai Volcano. The main geologic feature on this portion of the Island of Molokai is the eastward trending rift zone, which is suggested by Fiske and Jackson (1972) to extend away from the caldera complex of the East Molokai Volcano toward the coastline to the mouth of Halawa Valley. A mapped volcanic cone near Koalii (Stearns and Macdonald,1947) is also located in the study area.

The main objective of the geophysical survey was to assist in characterizing the hydrologic regime at the Puu o Hoku Ranch site for a proposed groundwater well. Groundwater resources can occur on the Island of Molokai basically in two modes:

- In a basal mode, where a lens-shaped body of fresh water floats on saline water, and
- In a high-level mode, where the groundwater occurrence is controlled by subsurface damming structures.

These two types of groundwater occurrences are illustrated in Figure 1-2. The surficial volcanic rocks in an island setting are generally highly permeable, and this allows rainwater to infiltrate directly downward through the island mass. The basal ground-water lens extends from the outer edges of subsurface structures (i.e., impervious dikes) to a discharge area near the shoreline. The subsurface structures can impede the flow of groundwater from the interior of the island toward the sea and result in fresh water-filled compartments that can extend above and below sea level. These types of occurrences are referred to as high-level ground water on the Hawaiian Islands. At the Puu o Hoku Ranch study area, groundwater was expected to occur mainly as a basal fresh-brackish water lens.

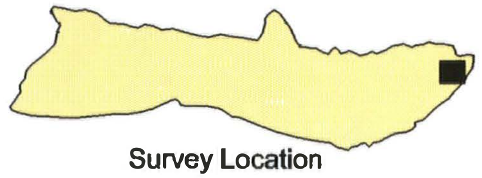
Previous TDEM surveys on the Hawaiian Islands have reliably mapped the boundary between fresh water in the basal mode and high-level water occurrences. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for well placement and completion depths.



Explanation

1	TDEM Soundings
A-A'	Section Line
WT	Water Tank

Island of Molokai



Survey Location

0 2000 4000 6000
Scale in Feet
Contour Interval 20 Meters

True North
11.5°
Magnetic North

BLACKHAWK GEOMETRICS
Location Map
Puu o Hoku Ranch Site
Puu o Hoku Ranch, Ltd.
Island of Molokai, Hawaii

Project No. 9912 Figure: 1-1

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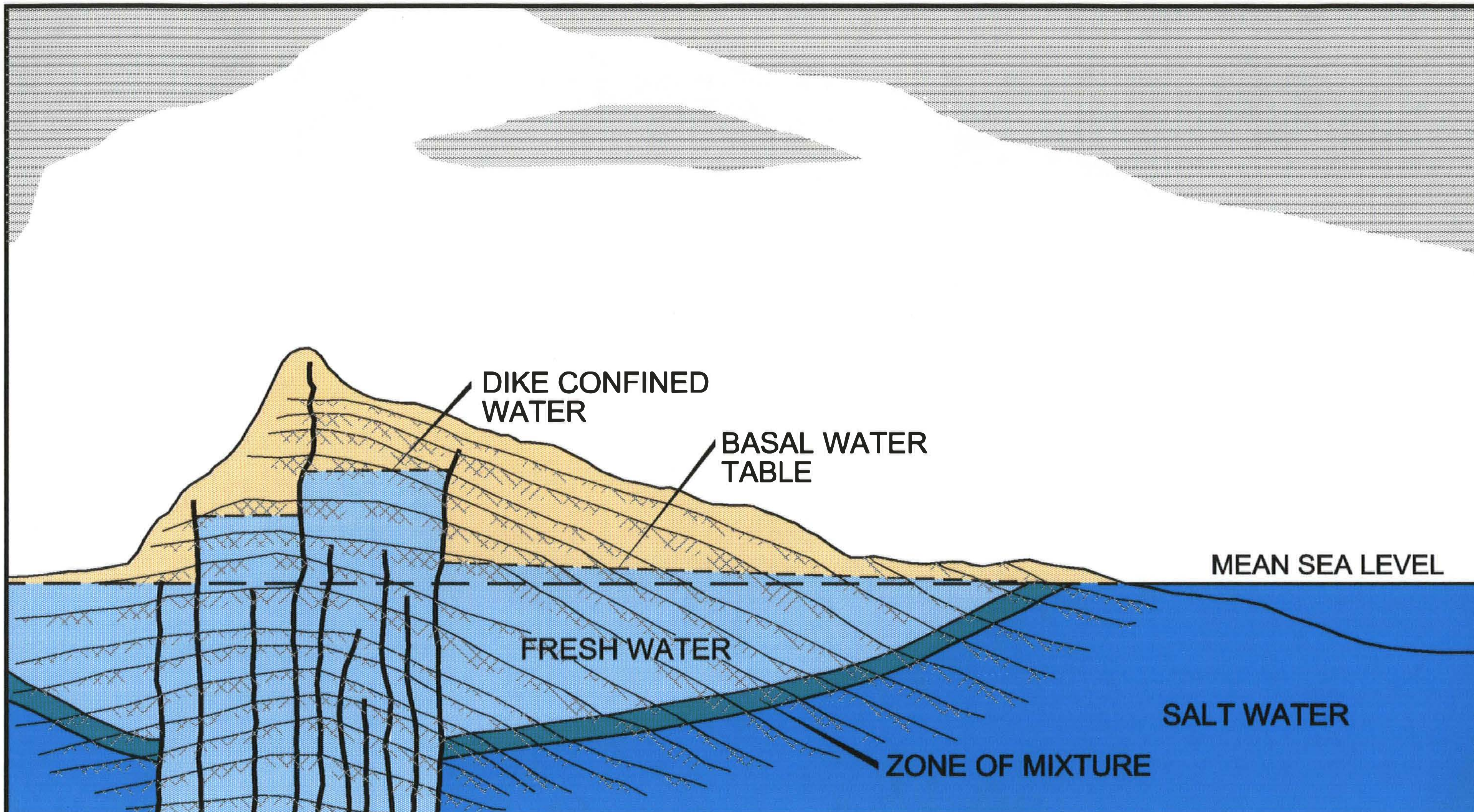

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Schematic
Hydrogeologic Cross Section

Puu o Hoku Ranch, Ltd.
Island of Molokai, Hawaii

Project No. 9912 Figure: 1-2

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2.0 DATA ACQUISITION AND LOGISTICS

The geophysical equipment utilized for the Time-Domain Electromagnetic (TDEM) surveys was the Geonics EM37 System. The EM37 system consists of both a portable transmitter (Tx) and receiver (Rx). TDEM measurements at Puu o Hoku Ranch were acquired using a central-loop sounding array at each site. With this array, data are recorded with a Rx coil at the center of nongrounded square Tx loops laid on the ground surface. The Tx loops were constructed with 12-gauge insulated copper wire. The dimensions of the Tx loops varied depending upon the exploration depth required at each site (larger loop dimensions for deeper exploration depth). The dimensions of the Tx loops at each site varied from 500 ft by 500 ft to 800 ft by 800 ft. The 2.8 kilowatt (kW) Tx was placed in each sounding loop to drive current ranging between 16.5 and 19.5 amperes at base frequencies of 3 and 30 hertz (Hz). At the center of each Tx loop, the time derivative of the vertical magnetic field was recorded with a circular Rx coil with an effective area of 100 m^2.

For data quality control comparisons, offset measurements were also made at designated locations near the center of each sounding. The data acquired at each sounding consisted of measurements at five different receiver gain settings and two transmitter frequencies in order to assure data quality and to obtain data over the largest possible time interval. The data from each sounding was stored in the field in an Omnidata polycorder with solid state memory and, subsequently, transferred to a personal computer (PC) for nightly processing. A technical note describing the principles of TDEM with case histories is given in Appendix A.

TDEM sounding loop locations were tied to known landmarks (i.e., water tanks, roads) with a hip-chain and compass and were plotted on the Molokai East topographic map. The sounding loop locations were selected by representatives of Puu o Hoku Ranch and Blackhawk. The loop locations were based on available open land and exploration objectives. A total of nine (9) TDEM soundings were acquired during the survey. The elevation of each sounding center was measured using an Altimeter/Barometer. The altimeter was set daily at the main water tank (elevation 918 ft, 280 m) for Soundings 1,2,3, and 5, while the Kuala benchmark (669 ft, 204m) was used for elevation checks for the remainder of the soundings. A daily log of field activity during the survey is given in Table 2-1.

TABLE 2-1 DAILY LOG OF FIELD ACTIVITIES	
DATE, 1998	**ACTIVITY**
December 1	Pack-up and mobilize geophysical equipment from Golden, CO, to Kaunakakai, Molokai, HI.
December 4	Mobilize Blackhawk Geometrics personnel from Golden, CO, to Honolulu, HI. Contact Puu o Hoku Ranch manager about geophysical equipment and coordinate travel with consulting hydrologist.
December 5	Mobilize Blackhawk personnel from Honolulu, HI, to Kaunakakai, Molokai, HI. Meet with Puu o Hoku Ranch manager and consulting hydrologist, discuss geophysical survey and recon Tx loop sites. Unpack and organize TDEM equipment into field vehicle. Lay-out Tx loop on Sounding 1 and acquire data. Process data at night.
December 6	Take TDEM data on Soundings 2 and 3. Perform data processing at night. Discuss results with consulting hydrologist, determine that additional data is needed.
December 7	Acquire data on Soundings 5,6, and 4. Process data at night and discuss results with consulting hydrologist. Decide to take more sounding data.
December 8	TDEM data on Soundings 7,8, and 9. Process data and determine that data acquisition is complete.Charge for half-day field work.
December 9	Pack-up geophysical equipment for freight pick-up at ranch. Demobilize Blackhawk Geometrics crew from Molokai, HI, to Honolulu, HI.
December 10	Personal day off, no charges.
December 11	Demobilize Blackhawk Geometrics personnel from Honolulu, HI, to Golden, CO.
December 14	Unpack geophysical equipment in Golden, CO.

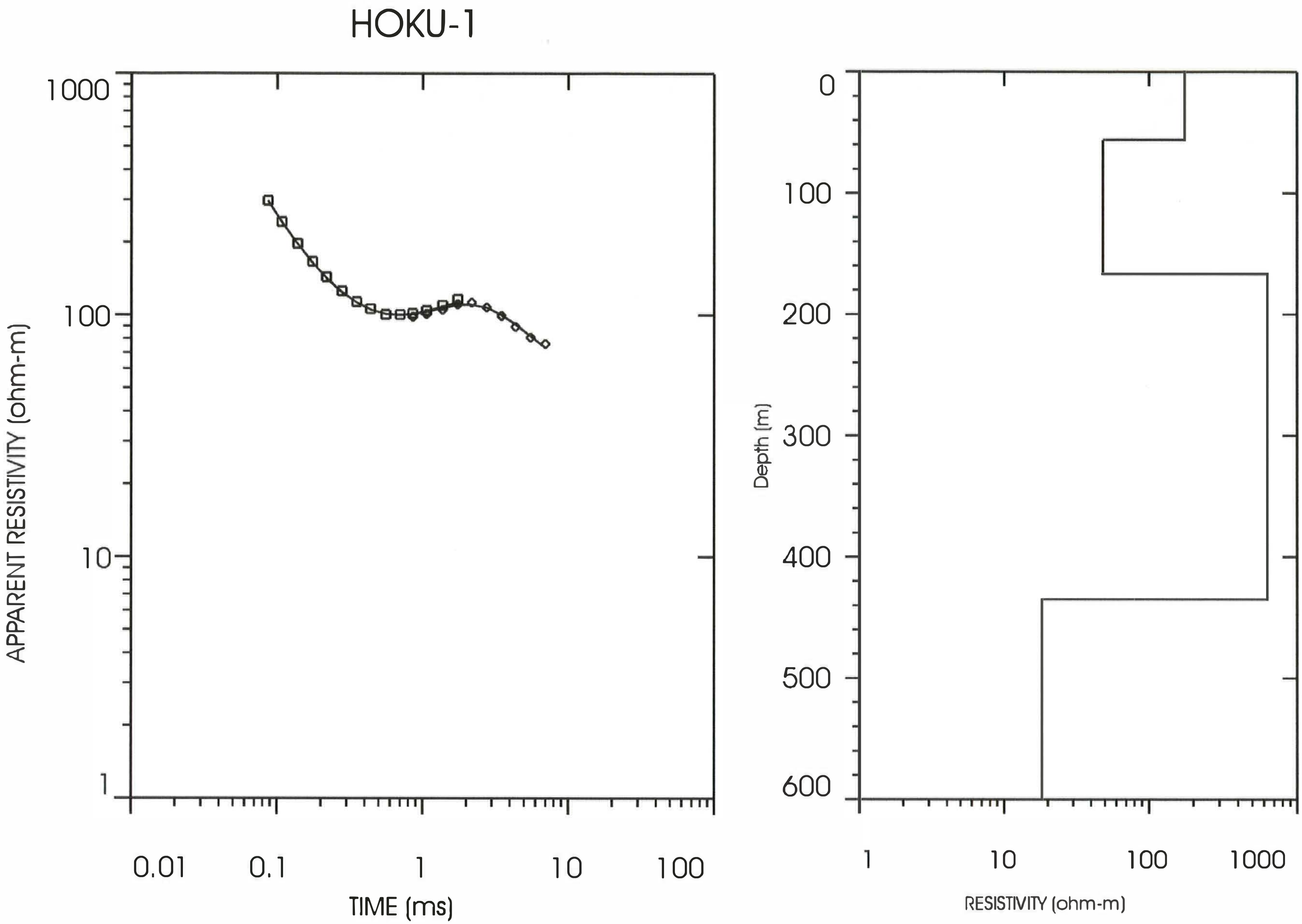
3.0 DATA PROCESSING

The TDEM field data acquired each day were uploaded from the polycorder solid state memory to a PC. Processing of the TDEM data includes the averaging of the electromotive forces (emfs) recorded at positive and negative receiver polarities. The measurements made at each sounding using several amplifier gains, and frequencies were combined to give one transient decay curve for the inversion program TEMIXXL (Interpex Ltd.). With this program, voltages are transformed into apparent resistivity verses time gate. The apparent resistivity curve is interpreted by inversion to a one-dimensional (1-D) geoelectric section that best matches the observed decay curve.

The TEMIXXL inversion program requires an initial solution of the geoelectric section measured. The initial solution includes the number of layers and the resistivities and thicknesses for each of the layers. The program then adjusts these parameters so that the model curve converges to best fit the curve formed by the field data. The inversion program does not change the number of layers within the model, but allows all other parameters to change freely, or they can optionally be fixed constant. To determine the influence and best fit of the number of layers on the solution, separate inversions with different (increased and decreased) numbers of layers are run. Normally, the model with the fewest number of layers which best fits the field data is used.

An example of the output of the inversion program for Sounding Hoku-1, is shown on Figures 3-1 and 3-2. Figure 3-1 shows the measured data points (in terms of apparent resistivity) superimposed on a solid line. The solid line represents the computed forward model of the geoelectric section shown on the right. Figure 3-2 shows the tabulated inversion parameters and model results consisting of measured field data, computed data for the best match solution, and inversion fitting error. A four-layer solution model is shown for Sounding Hoku-1. A discussion of the model results for each sounding is given in the following section.

The apparent resistivity curves and data sheets for all the TDEM soundings are given in Appendix B.



BLACKHAWK GEOMETRICS

TDEM Inversion Results
Sounding Hoku-1
Puu o Hoku Ranch, Ltd.
Island of Molokai, Hawaii

Figure: 3-1

Project No. 9912

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DATA SET: HOKU-1

CLIENT: PUU O HOKU RANCH
LOCATION: MOLOKAI, HAWAII
COUNTY: MAUI
PROJECT: PUU O HOKU RANCH
DATE: 12-05-98
SOUNDING: 1
ELEVATION: 290.00 m
EQUIPMENT: Geonics PROTEM
LOOP SIZE: 244.000 m by 244.000 m
AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y)
TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 100.0000 N: 1.0000
SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 2.203 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(ft)	CONDUCTANCE (Siemens)
			290.0	951.4	
1	174.6	55.96	234.0	767.7	0.320
2	48.34	110.8	123.1	403.9	2.29
3	635.9	268.2	-145.0	-475.7	0.421
4	18.32				

ALL PARAMETERS ARE FREE

CURRENT: 18.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 4 RAMP TIME: 160.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	47288.4	47101.1	0.396
2	0.108	37090.5	36834.7	0.689
3	0.138	27421.3	27318.5	0.374
4	0.175	19610.8	19816.5	-1.04
5	0.218	14093.6	14257.1	-1.15
6	0.278	9397.5	9493.5	-1.02
7	0.351	6118.2	6149.3	-0.508
8	0.438	3887.7	3905.1	-0.448
9	0.558	2296.4	2269.1	1.18
10	0.702	1296.9	1300.6	-0.285
11	0.858	773.8	775.9	-0.273
12	1.06	431.2	432.6	-0.313
13	1.37	213.6	216.6	-1.40

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	1.74	107.6	112.3	-4.37

CURRENT: 18.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 160.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	0.857	809.7	783.0	3.29
16	1.06	450.8	437.1	3.03
17	1.37	227.1	220.9	2.72
18	1.74	115.0	116.3	-1.13
19	2.17	64.71	66.72	-3.09
20	2.77	37.66	37.84	-0.475
21	3.50	23.72	23.40	1.34
22	4.37	15.92	15.27	4.08
23	5.56	10.16	9.92	2.41
24	6.98	6.29	6.60	-4.91

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	P 3	P 4	T 1	T 2	T 3
P 1	0.22						
P 2	0.04	0.88					
P 3	0.01	-0.01	0.01				
P 4	-0.04	0.08	-0.03	0.49			
T 1	0.29	0.10	0.00	-0.05	0.76		
T 2	-0.07	-0.16	-0.07	0.14	0.19	0.74	
T 3	-0.02	0.01	0.06	0.07	0.00	0.01	0.97

BLACKHAWK GEOMETRICS

TDEM Inversion Results
Sounding Hoku-1
Puu o Hoku Ranch, Ltd.
Island of Molokai, Hawaii

Figure: 3-2

Project No. 9912

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4.0 INTERPRETATION RESULTS

4.1 General

The primary objective of the TDEM soundings is to derive the resistivity layering (geoelectric section) of the subsurface. The translation of resistivity layering into hydrologic information is generally accomplished by two methods. These include:

1) Using available knowledge about the relation between resistivity values and local hydrology. From more than 40 previous TDEM surveys on the Hawaiian Islands, it has been observed that volcanic rocks saturated with salt water exhibit resistivities typically less than 5 ohm-m. Conversely, volcanic rocks that are dry and unweathered or fresh water saturated, exhibit high resistivities (generally greater than 500 ohm-m). Weathered volcanics or ash flows and intrusives often exhibit intermediate resistivities (about 10 ohm-m to 100 ohm-m). Generally, it is difficult to discriminate between dry volcanic rocks and fresh-brackish water (less than 250 ppm chloride) saturated volcanic rocks. The main reasons are that, in addition to salinity, changes in porosity and lithology also influence formation resistivity.

   Applying this information, characteristic ranges of resistivities expected for local hydrogeologic units for the Puu o Hoku Ranch site are shown in Figure 4-1. It should be noted that some overlap in resistivity values occur. In these cases, other factors are used to infer the geologic/hydrologic unit in question. For example, a low resistivity unit (i.e., less than 10 ohm-m) occurring at an elevation above sea level is assumed to be caused by either weathered rock units or intrusives (i.e., dikes) instead of salt water saturated formations.

2) Another method is to calibrate the geophysical interpretation at a well. At the time of this study, there was no well information available for comparison to the TDEM data in the vicinity of Puu o Hoku Ranch.

In a TDEM measurement where a very conductive layer (less than 5 ohm-m) is detected below sea level, the conductive layer is interpreted to be caused by salt water saturated volcanics. Static fresh water levels (head) can be calculated from these soundings by using the Ghyben-Herzberg relation as illustrated in Figure 4-2. The Ghyben-Herzberg relationship states that for every 1 ft of fresh water above sea level, approximately 40 ft of fresh water will exist below sea level. However, hydrostatic equilibrium is assumed for these measurements, and this relationship is not expected to apply to soundings in close proximity to geologic structures (i.e., dikes, rift zones) which can disrupt ground water flow. The 1-D modeling program is based on the assumption that resistivity changes occur with depth (i.e., horizontally layered earth). Lateral changes in resistivity can occur between soundings due to vertical dikes, intrusives or other geologic features. When these non-1-D conditions occur, the modeled geoelectric section may not represent true formation resistivities.

4.2 Geoelectric Cross Sections

The results of the inversion of the individual TDEM soundings is the 1-D resistivity layering as a function of depth. The results from the individual soundings can be linked together to produce a 2-D geoelectric cross section along a survey transect. The geoelectric cross section can be correlated to geologic units by comparison with available geologic information. Two geoelectric cross sections were constructed from the Puu o Hoku Ranch data set. The locations of the geoelectric cross sections are shown on Figure 1-1.

Cross Section A-A'

Figure 4-3 shows the results of four TDEM soundings (1,2,3, and 6) presented as a West to East trending geoelectric cross section (A-A') in which layers that exhibit similar resistivity values have been linked together. Four-layer geoelectric sections are modeled for each of the soundings.

The upper two layers of the cross section (green) display resistivities ranging from about 17 ohm-m to 218 ohm-m. These two layers are interpreted to represent weathered surficial volcanics beneath all soundings. The weathered volcanic layers range in thickness of about 350 ft beneath Sounding 6 to 540 ft beneath Sounding 1. The third layer in the geoelectric section exhibits resistivities ranging from 335 ohm-m to 748 ohm-m. This layer is interpreted to represent dry unweathered volcanics above sea level; and where it occurs below sea level, it is expected to be saturated with fresh-brackish basal mode water. Beneath Soundings 3 and 6, the lower layer (blue) exhibits resistivities of 2.5 and 2.7 ohm-m and is interpreted to represent salt water saturated volcanics. The estimated thickness of the fresh-brackish lens resting on seawater at these two soundings varies from approximately 376 ft beneath Sounding 3 to 329 ft beneath Sounding 6.

Soundings 1 and 2 did not detect seawater to an approximate exploration depth of 750 ft below sea level. These two soundings are interpreted to be located in a structurally complex area of the site. Beneath Soundings 1 and 2 at depth, intermediate resistivity values of 18 to 57 ohm-m (green) are interpreted, and they are expected to be caused by influences from lateral discontinuities (e.g., dikes, faults, etc.). Because of the rapid lateral variations in resistivities, the interpreted stratification may not represent true formation resistivities beneath these two soundings. The exact position and width of the discontinuity is uncertain due to the TDEM station density. Therefore, since the salt water interface was not interpreted to occur beneath Soundings 1 and 2, the elevation of the ground water table can not be estimated using the Gyben-Herzberg relation.

However, from the geoelectric cross section, the depth to the top of the intermediate resistivity boundary increases from Sounding 2 (176 ft BSL) toward Sounding 1 (476 ft BSL). This suggests that the likelihood of a potential lens of fresh water below sea level would be greater beneath Sounding 1 than Sounding 2.

Cross Section B-B'

The geoelectric cross section B-B' is shown on Figure 4-4. In all the soundings, surface volcanic layers (green) with resistivities ranging from about 9.8 ohm-m to 221 ohm-m are present. The upper more resistivity cap layer present in all other soundings appears to have been eroded away at Sounding 9. The thickness of the surface layer varies from 100 ft at Sounding 9 to about 330 ft beneath Soundings 7 and 8. The next layer in the section exhibits resistivities ranging from about 93 ohm-m to 930 ohm-m. This layer is interpreted to represent unweathered volcanics above sea level; and where it occurs below sea level, the layer is expected to be saturated with fresh-brackish basal water. At the base of all the soundings, a low resistivity layer (blue) is mapped. This lower layer is interpreted to represent salt water saturated volcanics with resistivities ranging from 2.3 ohm-m to 2.8 ohm-m. The thickness of the fresh-brackish water lens can be calculated using the Ghyben-Herzberg relation and is estimated to be 83 ft beneath Sounding 9 near the shoreline, and 433 ft beneath Sounding 7. The unusually thick lens of basal water interpreted beneath Sounding 7, may be the result of increased permeability and porosity of the volcanic formations in this area which is causing a depression of the seawater. No subsurface structures were interpreted beneath these four TDEM soundings.

4.3 Hydrogeologic Interpretation

For seven of the nine TDEM soundings from the Puu o Hoku Ranch site, salt water saturated volcanics were detected below sea level. The fresh-brackish water resource can be estimated in these soundings by the volume between sea level and the interpreted elevation of the salt water interface, plus the head calculated from the Ghyben-Herzberg relation. Table 4-1 shows the thickness of the fresh-brackish water lens interpreted directly from the model results for each sounding.

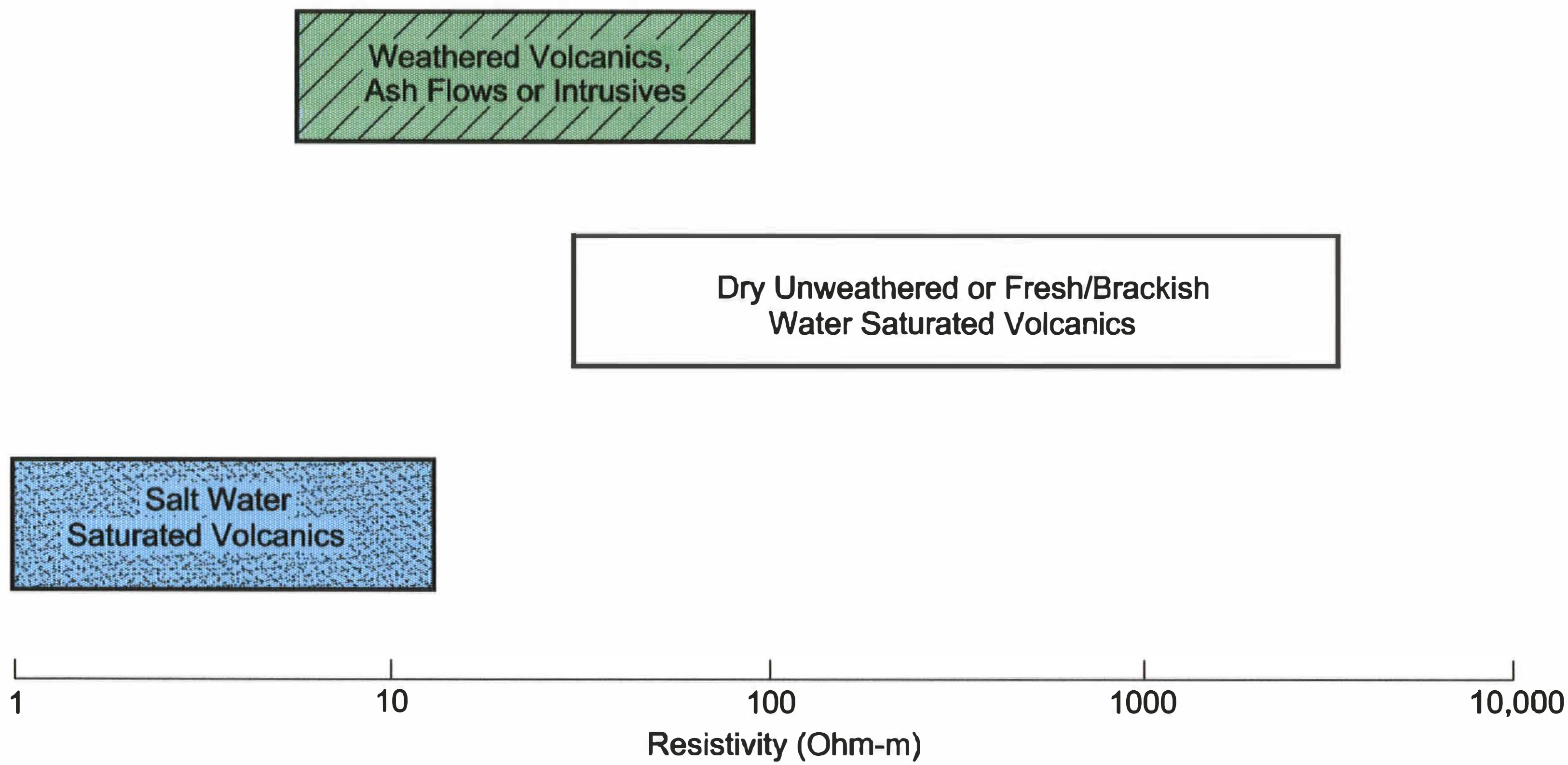
TABLE 4-1
HYDROGEOLOGIC INFORMATION
DERIVED FROM TDEM SOUNDINGS

Sounding Number	Surface Elevation (ft)	Estimated Thickness of Fresh-Brackish Water Lens (ft)
1	951	*
2	1060	*
3	735	385.4
4	673	333.9
5	860	324.8
6	669	337.6
7	597	444.2
8	597	344.3
9	180	85.4

*Basal salt water interface not detected.

The accuracy of determining the depth to the salt water interface from TDEM soundings is estimated to be ±5% of the total depth calculated in the sounding result (e.g., from the ground surface to the salt water interface).

The results of the TDEM investigations at the Puu o Hoku Ranch site are further summarized in the interpretation summary map shown in Figure 4-5. This map shows the seven soundings (3 though 9) in which the ground water is interpreted in the basal mode (blue). Also shown are Soundings 1 and 2 (green), which are interpreted to be influenced by lateral discontinuities (i.e., intrusives, dikes, etc.). The boundary of an inferred geologic/hydrologic discontinuity is placed below Soundings 1 and 3, which appears to define a subsurface geologic structure (i.e., dikes, intrusives), which may be a localized feature or related to the East Rift Zone.



BLACKHAWK GEOMETRICS

Characteristic Resistivity Ranges of Hydrologic Units

Puu o Hoku Ranch, Ltd.
Island of Molokai, Hawaii

Project No. 9912	Figure: 4-1

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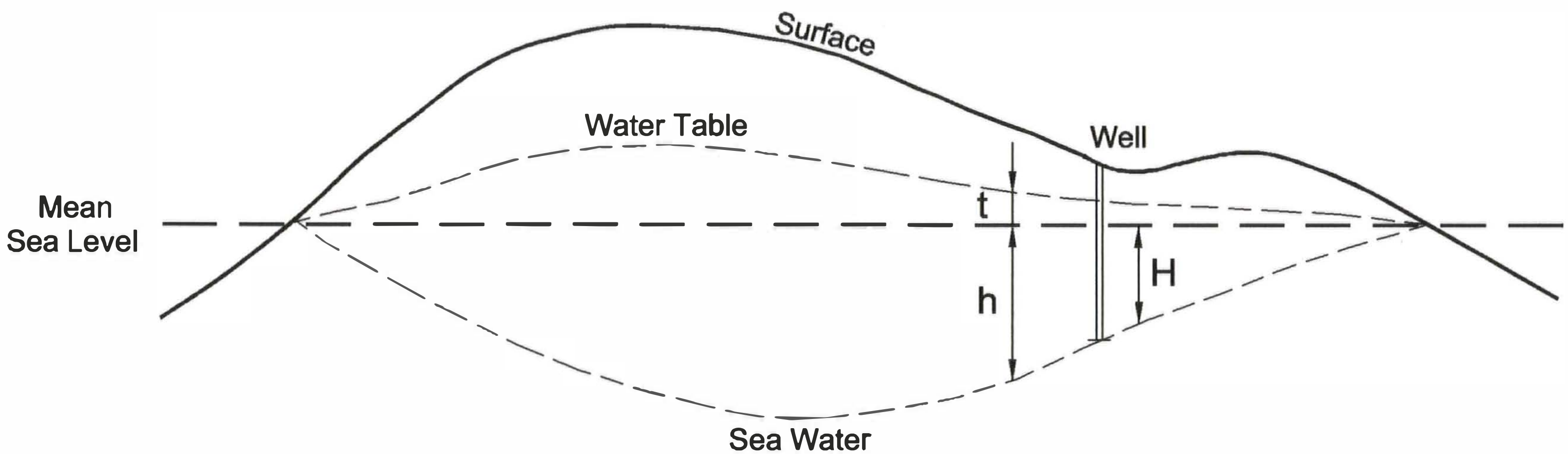

$t = 1/40\ (h)$

From: Herzberg

BLACKHAWK GEOMETRICS

Illustration of the Ghyben-Herzberg Principle

Puu o Hoku Ranch, Ltd.
Island of Molokai, Hawaii

Project No. 9912	Figure: 4-2
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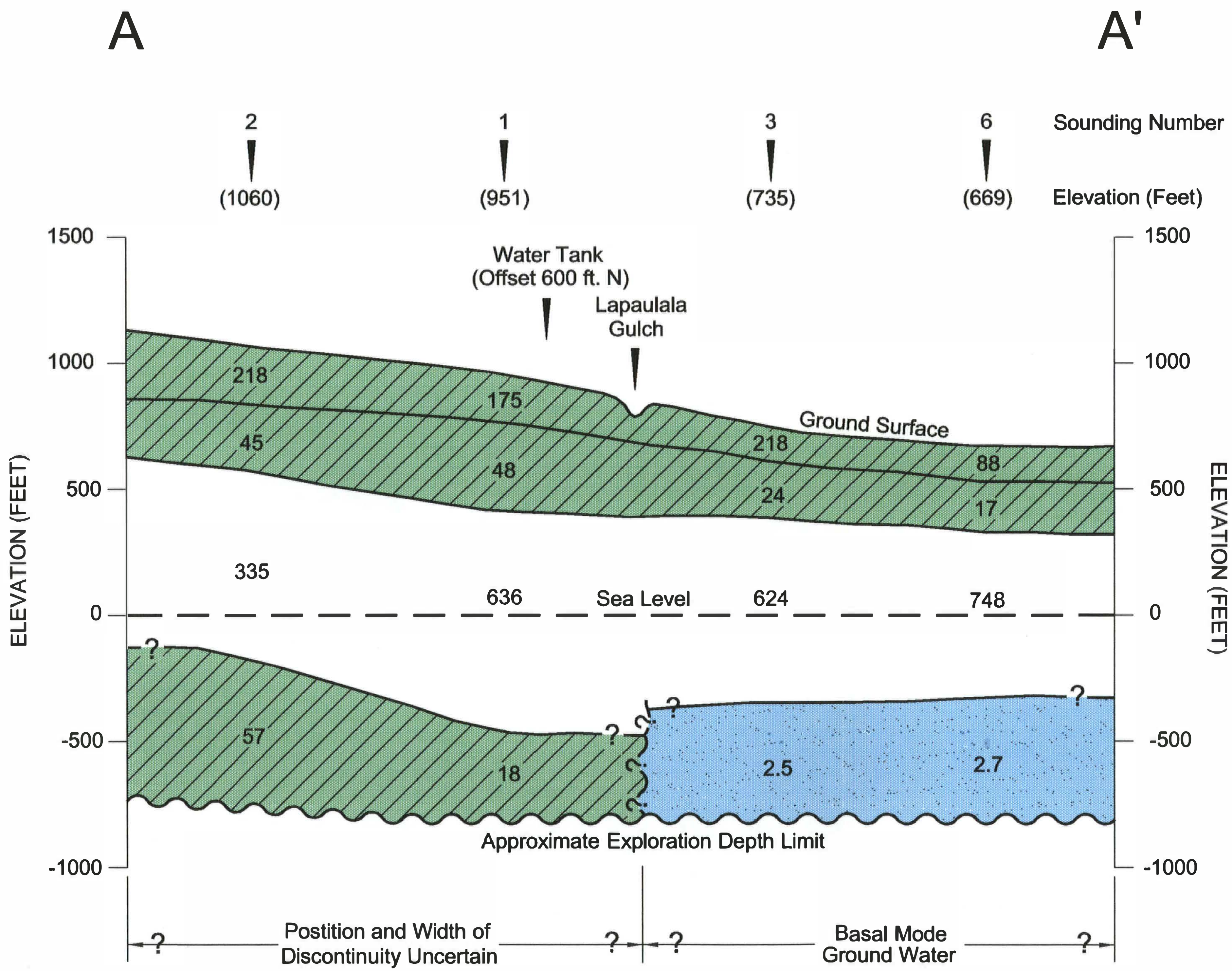

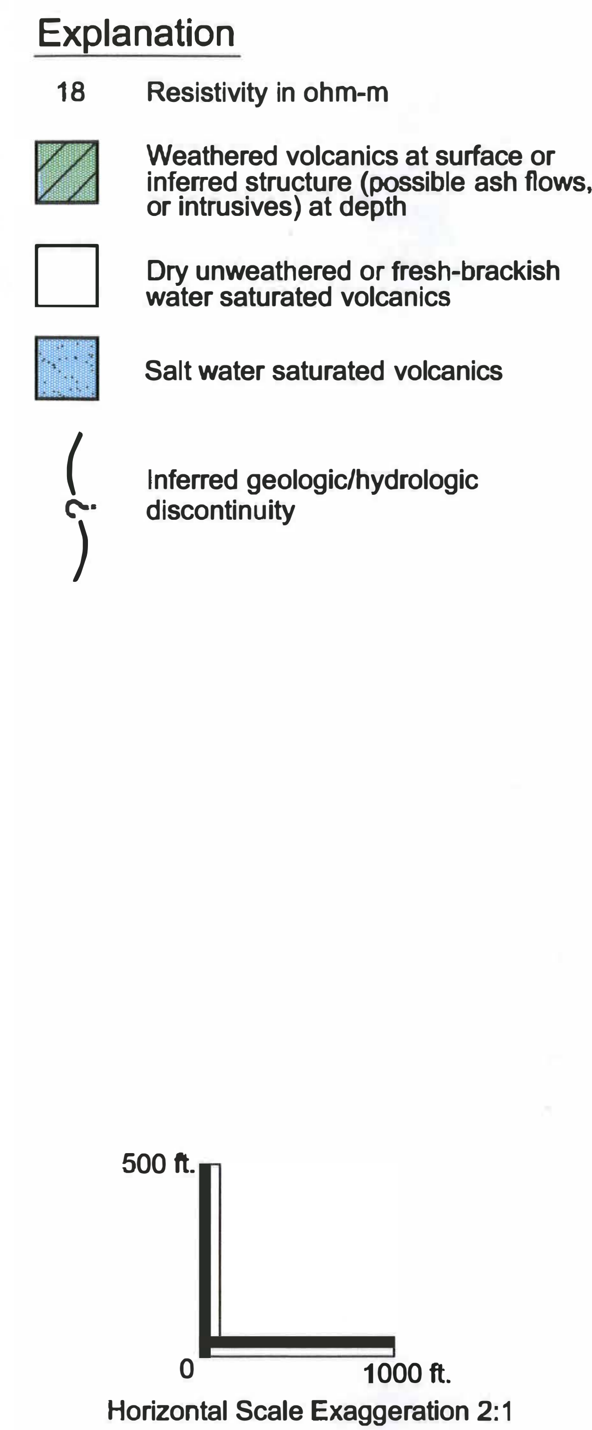

BLACKHAWK GEOMETRICS

Geoelectric
Cross Section A-A'
Puu o Hoku Ranch Site

Puu o Hoku Ranch, Ltd.
Island of Molokai, Hawaii

Project No. 9912 Figure: 4-3

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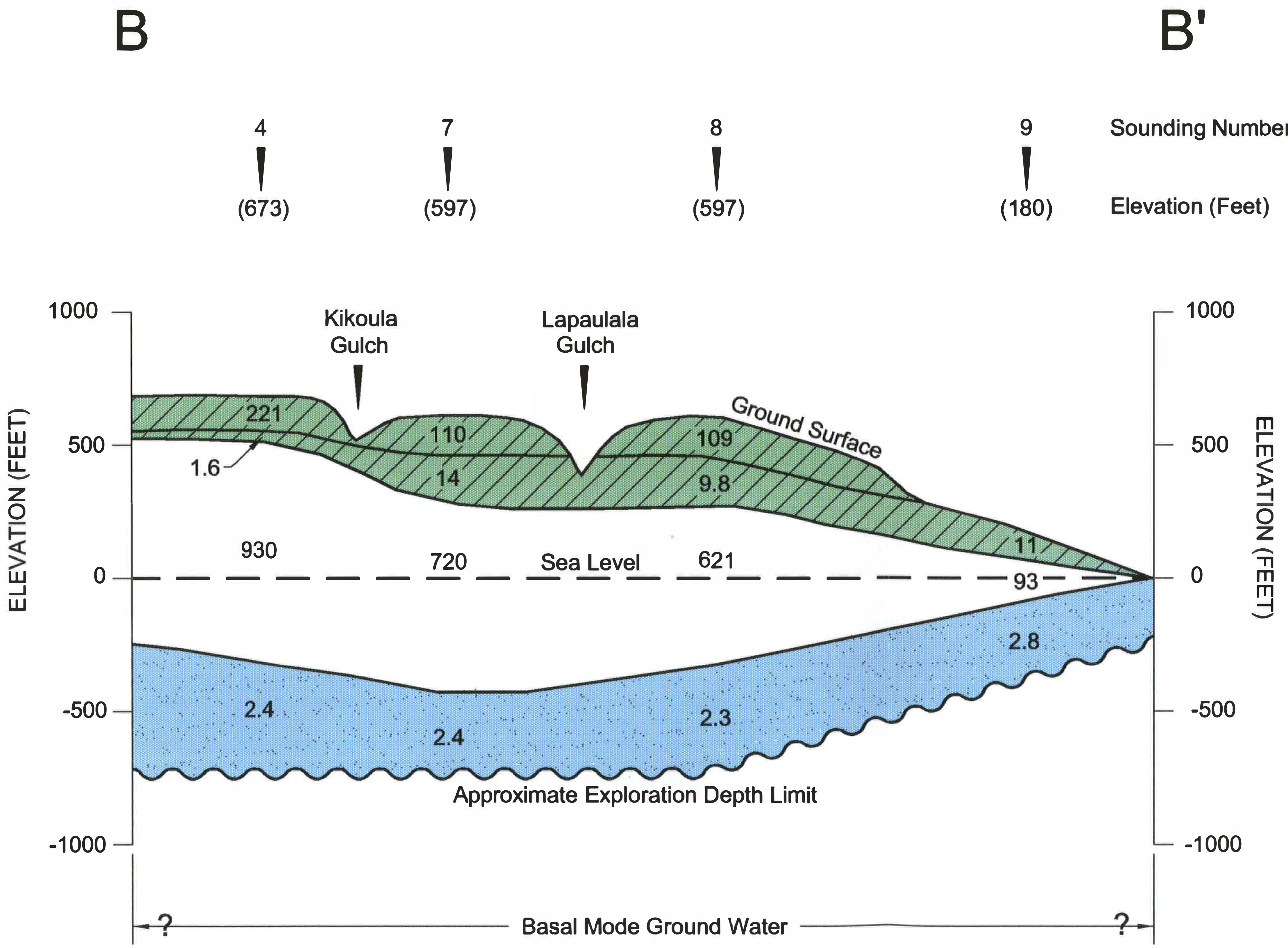

Explanation

14 Resistivity in ohm-m

Weathered volcanics at surface or inferred structure (possible ash flows, or intrusives) at depth

Dry unweathered or fresh-brackish water saturated volcanics

Salt water saturated volcanics

Inferred geologic/hydrologic discontinuity

500 ft.
0
1000 ft.
Horizontal Scale Exaggeration 2:1

BLACKHAWK GEOMETRICS

Geoelectric Cross Section B-B'
Puu o Hoku Ranch Site
Puu o Hoku Ranch, Ltd.
Island of Molokai, Hawaii

Project No. 9912 Figure: 4-4

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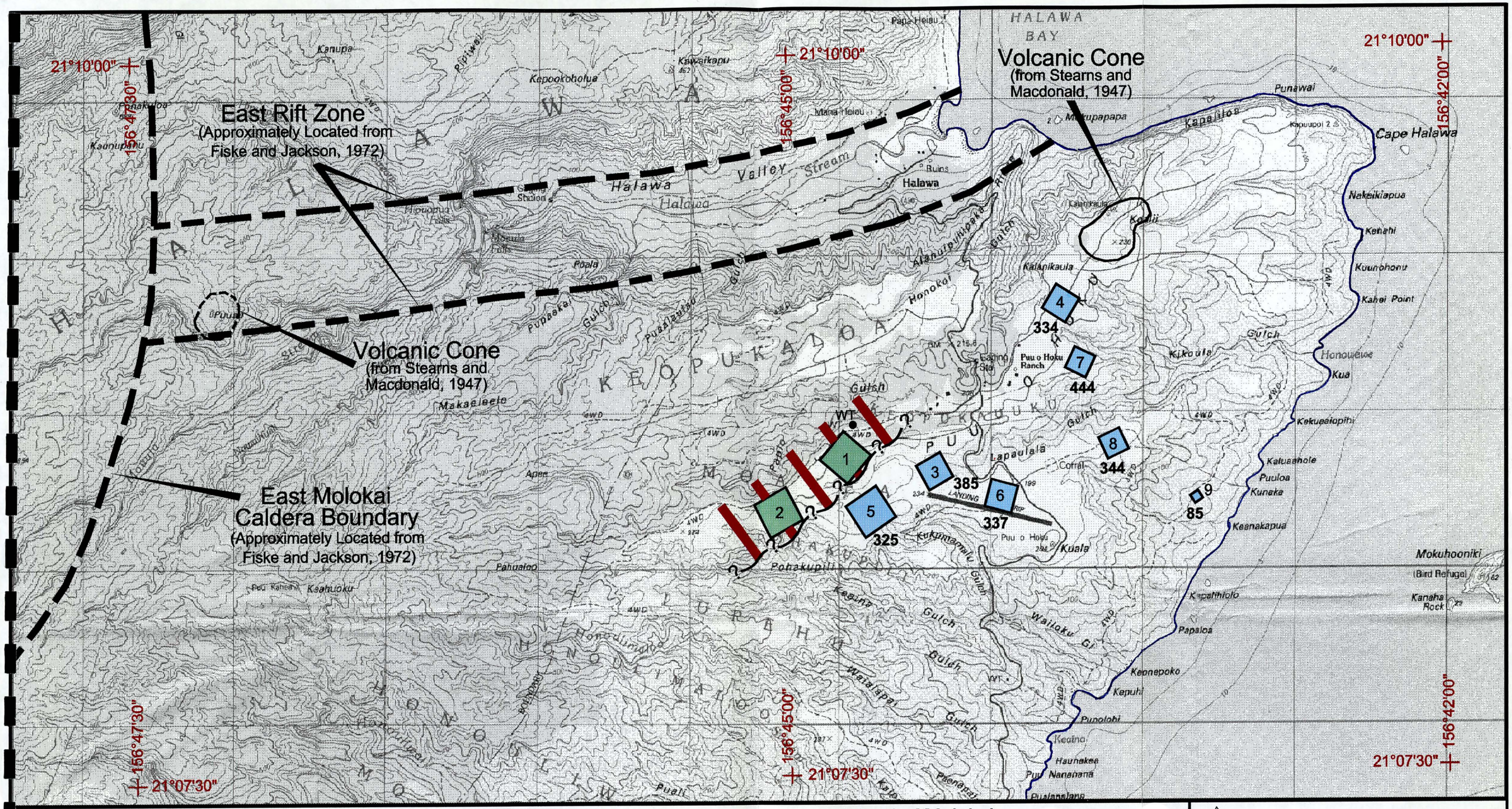
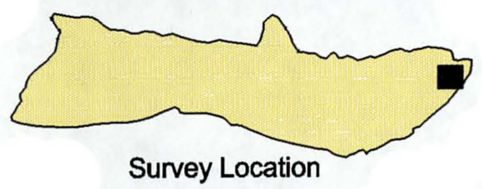


Explanation

3	Sounding in which ground water is expected in basal mode
1	Sounding influenced by lateral discontinuity (dikes, faults)
325	Estimated thickness of fresh-brackish lens in feet
	Inferred geologic/hydrologic discontinuity (exact position uncertain)



0 2000 4000 6000

Scale in Feet

Contour Interval 20 Meters

True North 11.5° Magnetic North

BLACKHAWK GEOMETRICS

Summary Map
Puu o Hoku Ranch Site

Puu o Hoku Ranch, Ltd.
Island of Molokai, Hawaii

Project No. 9912 Figure: 4-5

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5.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the TDEM surveys at the Puu o Hoku Ranch site on the east side of the Island of Molokai indicate that beneath seven of the nine soundings, a lens of basal mode fresh-brackish water occurs (Figure 4-5). In the vicinity of the main water tank (elevation 918 ft, 280 m) along section A-A', the data indicate that the thickest lens of potential fresh-brackish water resource is interpreted to occur beneath Sounding 3, and it is estimated to be 385 ft. Beneath Soundings 1 and 2, subsurface geologic structures (i.e., dikes, faults) are interpreted. The East Rift Zone is postulated to cross north of the survey area at about a N 85° E bearing through Halawa Valley. The potential for groundwater resources exists beneath Soundings 1 and 2 (Figure 4-3), but it is expected to be controlled by geologic structures. Groundwater yield, and quality in these areas may be highly variable. The ground water resources within areas controlled by geologic structures cannot be determined directly from the TDEM sounding data.

Downslope from the water tank (along section B-B'), groundwater resources are also expected to occur in the basal mode. The thickest lens of fresh-brackish water, along this geoelectric section is interpreted beneath Sounding 7, and is estimated to be 444 ft. This lens thickness appears to be anomalous for this elevation and proximity to the coastline, but TDEM Soundings 4 and 8 confirm the thick groundwater lens in this area.

Areas of potential high-level groundwater resources were not located during this study. If this is an objective at this study area, additional TDEM soundings are recommended above Sounding 2.

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Case Histories of Time-Domain Electromagnetic Soundings in Environmental Geophysics

Pieter Hoekstra and Mark W. Blohm**

Abstract

Time-domain electromagnetic (TDEM) soundings are a surface electromagnetic technique that finds increasing use in environmental geophysics. Commercial equipment is now available for TDEM soundings in the exploration depth range from about 5 m to about 5000 m. Application of TDEM is illustrated in three case histories.

The transmitter-receiver array used in all three investigations was the central-loop array, in which measurements of the electromotive force due to the vertical magnetic field are made with a receiver in the center of square, nongrounded transmitter loops. The dimensions of the transmitter loops were varied from 30 m by 30 m for effective exploration depths between 5 m to 75 m, to 500 m by 500 m for effective exploration depths to about 2500 m. These relatively small dimensions of receiver/transmitter arrays, compared to the exploration depth, allow TDEM surveys to be made in urban areas where open spaces are limited in size, and where environmental and ground-water problems are perhaps most urgent. Also, the procedures of signal processing used in TDEM facilitate operation in the presence of high ambient electrical noise prevalent in urban settings.

The three case histories map:

(1) the depth of first occurrence of brine for assisting site evaluation of a high-level nuclear-waste repository in bedded salts near Carlsbad, New Mexico,

(2) the encroachment of salt water in a multiple-zone coastal aquifer system in the Salinas Valley, California, (The availability of about 100 monitoring wells allowed correlation of formation resistivities to ground-water salinity.) and

(3) shallow basalt flows in the exploration depth range from 5 m to 30 m. (This case history shows the results of TDEM measurements over the time range from about 10^{-6} s to 10^{-4} s with central-loop soundings of small (30 m) dimensions.)

Introduction

Time-domain electromagnetic (TDEM) soundings increasingly are being employed for determining geoelectrical sections. Reported applications of this TDEM method are in mapping of volcanic cover (Frischknecht and Raab, 1984; Keller et al., 1984), onshore and offshore permafrost (Ehrenbard et al., 1983), geothermal reservoirs (Fitterman et al., 1988), hydrocarbons (Rabinovich et al., 1977; Wightman et al., 1983), and ground water (Fitterman and Stewart, 1986; Mills et al., 1988). Theoretical aspects of the method, such as behavior of magnetic and electric fields (e.g., Nabighian and Oristaglio, 1984), definition of apparent resistivity (Kaufman and Keller, 1983; Spies and Eggers, 1986), transmitter-receiver arrays (Kaufman and Keller, 1983), and influence of two-dimensional (2-D) and three-dimensional (3-D) structures on one-dimensional interpretations (Hohmann, 1988; Newman et al., 1987) are discussed throughout the geophysical literature [see also McNeill, Vol. I—Ed.].

Several reasons are apparent for the increasing use of TDEM in environmental geophysics. In urban areas ambient electrical noise is high, and open spaces limited. TDEM surveys can often work around these limitations. Small transmitter-receiver arrays can be laid out in athletic fields, parks, and other open spaces, and ambient

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electrical noise due to residential power service can often be removed by stacking. Also, recent availability of equipment with fast, current ramp turn-off and early-time measurements bring shallow mapping objectives for ground-water protection and contaminant investigations within the exploration depth range of TDEM.

A limitation of TDEM at this time is the lack of practical, cost-effective algorithms for interpreting 2-D and 3-D structures. At present, forward modeling of 2-D and 3-D structures (Newman et al., 1987), requires significant central processing unit (CPU) time on the mainframes negating their application to shallow TDEM exploration. It is in the development of practical algorithms for 2-D and 3-D interpretations for personal computers that the main advances in TDEM must come.

Illustrated applications of the method to three environmental objectives include (1) assisting in siting of high-level, nuclear-waste repositories, (2) mapping the intrusion of salt water in coastal aquifers, and (3) mapping the thickness of thin basalt flows. The basic principles of the equipment and the procedures of data acquisition and processing are similar for all three case histories. Some characteristics of central-loop array measurements, such as land survey requirements, location of plotting points, and vertical resolution are reviewed briefly. Equipment design parameters and data acquisition, processing, and interpretation procedures are discussed. These principles are illustrated subsequently on the three case histories. The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories.

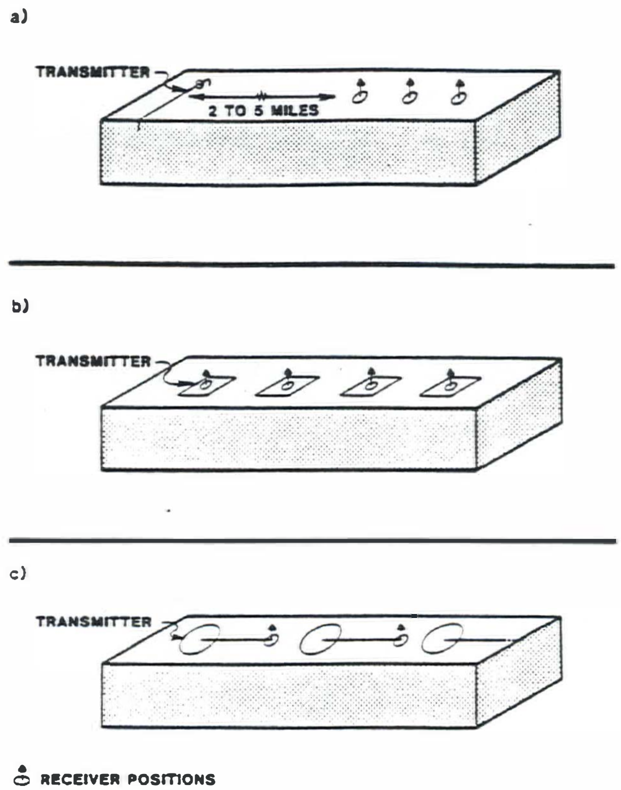

FIG. 1. Transmitter-receiver arrays, (a) grounded line, (b) central loop, and (c) loop-loop.

Practical Aspects of Data Acquisition

Transmitter-Receiver Arrays

The three types of transmitter-receiver arrays employed in TDEM soundings are illustrated in Figure 1. The array used in the three case histories is the central loop array (Figure 1b). For applications in environmental geophysics there are certain advantages to the central loop array, such as:

(a) Land survey and space requirements.—Figure 2 shows the measured behavior of the electromotive forces (emf's) due to horizontal (x) and vertical (z) magnetic field components on a profile through the center of a square transmitter loop at 2.2 ms after current turn-off. Data at other times would show a similar behavior but differ in amplitudes. The emf due to the z-component can be seen to be relatively flat about the center. Location errors of $\pm 10\%$ L (L is side of square) cause negligible errors, and deviations from a square transmitter loop have little effect on a data set. Because in central loop soundings the geoelectric section is derived from emf$_z$, requirements for accurate positioning are minimal which enhances the practical value of field survey productivity, and allows flexibility in choosing a station location. Because emf$_x$ has a zero crossing in the center of the loop, its measurement would require careful survey control. Also, ambient electrical noise is higher in horizontal components.

The dimensions of transmitter loops in central-loop arrays depend on required exploration depth, exploration objective, and geoelectric section. Optimum dimensions are generally selected from forward modeling and field tests. Typically, the length of a side of the transmitter loop is about two-thirds of the exploration depth for the EM-37. The EM-42 is generally employed for exploration depths from about 300 m to 2500 m with 500 m by 500 m transmitter loops, and with a grounded line array for deeper objectives.

The grounded line array (Figure 1a) with long offset receiver locations is dominantly used in deep electrical soundings in support of oil and gas exploration (Keller et al., 1984). The loop-loop array (Figure 1c) finds ap-

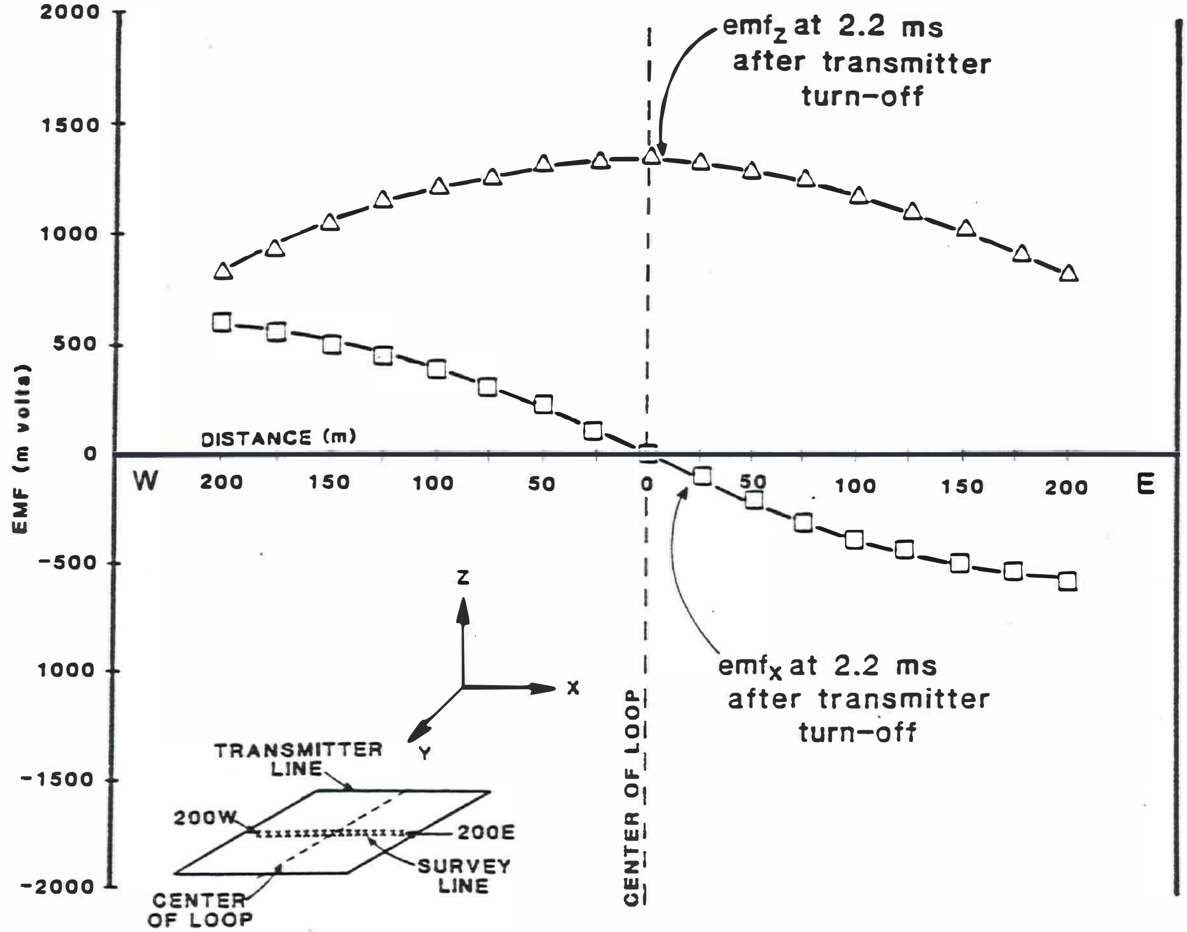

FIG. 2. Measured behavior of the electromotive forces due to vertical (emf$_z$) and horizontal (emf$_x$) magnetic fields on a profile through the center of a square transmitter loop.

plication in mineral exploration and in mapping of fractures and shear zones.

(b) Well-defined sounding plotting points.—The behavior of induced eddy currents and the resulting behavior of the secondary magnetic fields in horizontally-layered media are well documented (Kaufman and Keller, 1983; Ward and Hohmann, 1988). They show a current distribution diffusing downward and outward from the source. For nongrounded, square-loop transmitters currents are symmetrically distributed about the center. Therefore, the center is a well-defined plotting point.

In the grounded-line array or loop-loop array the entire section between transmitter and receiver is expected to influence the measurements, although subsurface conditions near the receiver may have a larger influence on emf$_z$ measured. The correct plotting point of a station is not well defined. Some place the plotting point below the receiver (Keller et al., 1984) and others midway between the transmitter and receiver (Rabinovich and Surkov, 1978). This same situation prevails in loop-loop arrays. In frequency-domain loop-loop arrays the midpoint of the array has traditionally been used as the plotting point.

(c) Vertical resolution.—Kaufman and Keller (1983) show that (1) the asymptotic behavior of emf$_z$ at late time, is given by

$$\text{emf}_z = \frac{\mu^{5/2}}{4\pi^{3/2}} \frac{\sigma^{3/2} M_t M_R}{t^{5/2}}; \qquad (1)$$

where

t = time after current turn-off,
σ = conductivity of uniform half-space,
μ = magnetic susceptibility,
M_t = moment of transmitter,
M_R = moment of receiver;

and (2) that this asymptotic expression describes the emf over the time range given by;

$$\frac{\tau}{R} > 16, \tag{2}$$

where

$$\tau \text{ is } \sqrt{\frac{8\,\pi^2 t}{\mu_0\,\sigma}}.$$

Figure 3 is a nomograph showing the onset of "late stage" behavior ($\tau/R > 16$), as a function of resistivity, and time at several values of R. Also shown on Figure 3 are the time ranges of measurement for the three systems used in the case histories. In central loop soundings typical values of R are between 15 m and 250 m, so that over a large time range of measurements emf$_z$ is proportional to $\sigma^{3/2}$. This high sensitivity of the quantity measured (emf$_z$) to the geoelectric section often results in a reduced range of equivalence for certain sections compared to other electrical and electromagnetic techniques (Fitterman et al., 1988).

Equipment

The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories. All three sets of equipment use the current waveform illustrated in Figure 4, consisting of equal periods of time-on and time-off. Figure 5 illustrates the difference in data acquisition between the EM-47 and EM-37, and the EM-42. In the EM-47 and EM-37 an analog stack is performed, and after completion of the stacking and A/D conversion, the data are stored in solid state memory. Normally, at the completion of a survey day, the data are transfered to a computer for data processing, plotting, and interpretation. During field operations no real-time processing is available. Minimum detectable signal in typical, urban, ambient-noise environments is 10^{-9} V/A-m^2 (normalized by current in transmitter loop, and effective area of receiver coil).

In the EM-42 the transient is sampled at 400 μs intervals, and these samples are digitally stored on 1/2-inch, 9-track tape. "Smart stacking" is applied to the data in real time. The minimum detectable signal with

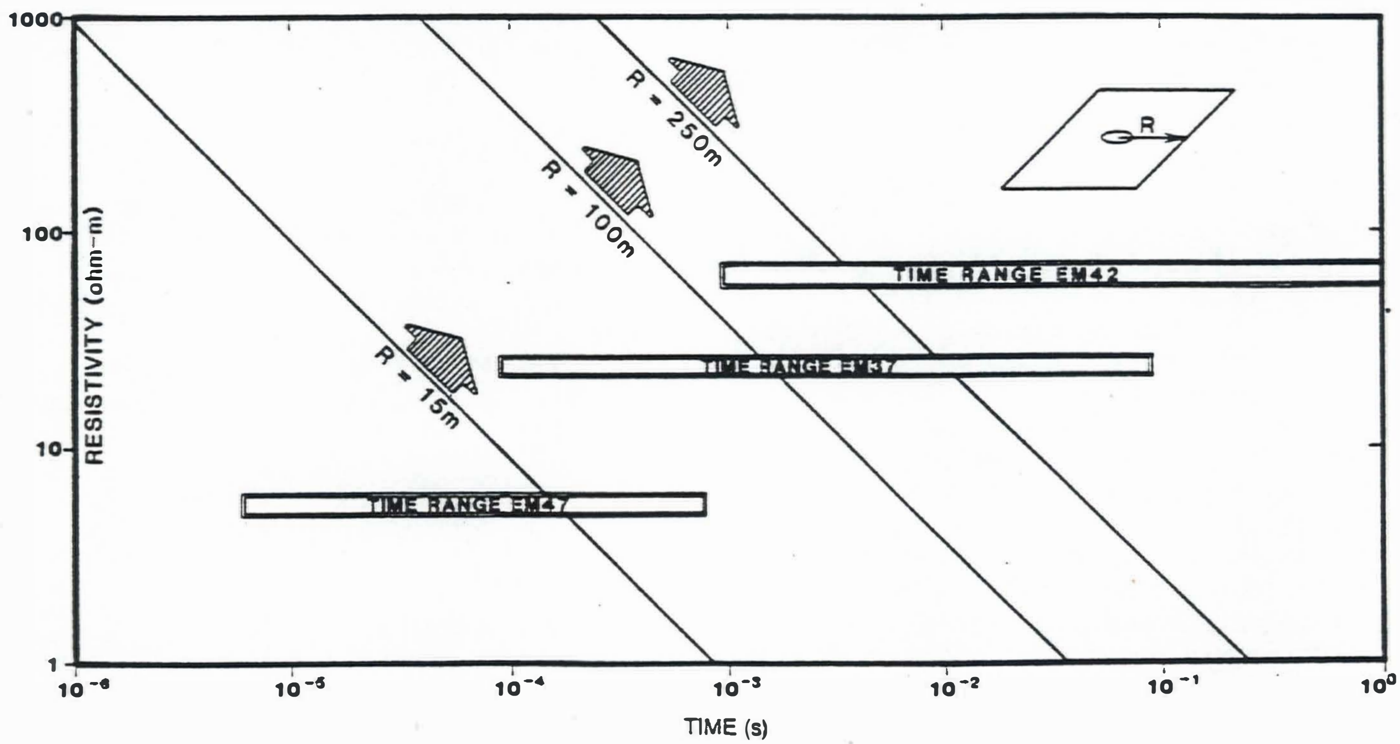

FIG. 3. Nomograph showing onset of late stage behavior for central-loop array as a function of time and resistivity of uniform half-space.

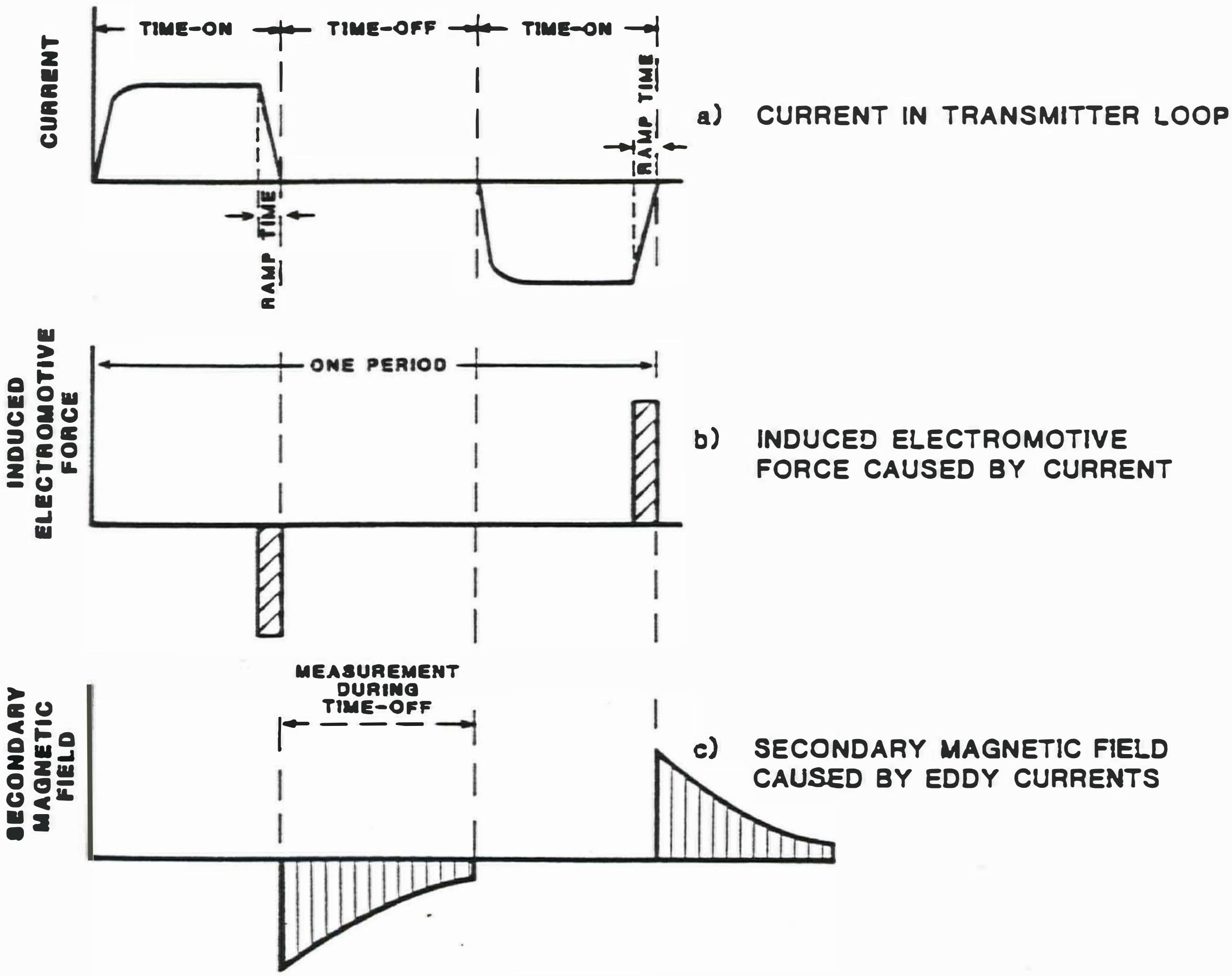

FIG. 4. System waveforms employed in Geonics EM-47, EM-37, and EM-42.

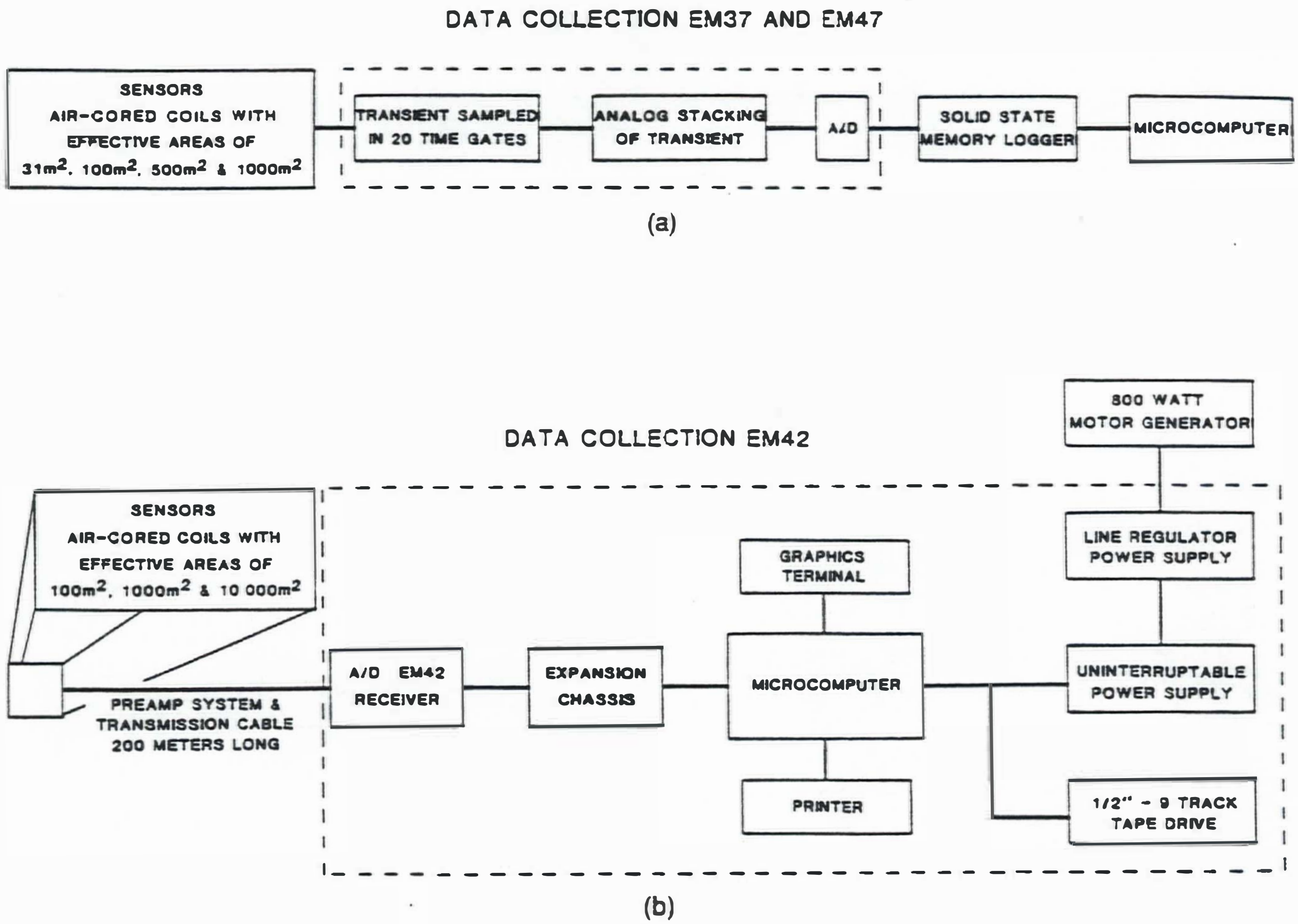

FIG. 5. Block diagrams of TDEM systems.

the EM-42 in typical ambient noise environments is 10^{-12} V/A-m^2

Data Acquisition

Recording transient decays with central loop soundings requires a large dynamic range, because emf$_z$ decays as $t^{-5/2}$, as shown in equation (1). This large dynamic range is often obtained by acquiring a data set in segments using different combinations of base frequencies, gains, and air coil receivers. An example of such a data set is given in Figure 6. The early time part of the curve was acquired at a base frequency of 3 Hz, 100 m^2 air coil and EM-37 receiver; the later time section was recorded with the EM-42 receiver, a 10 000 m^2 air coil and a base frequency of 0.075 Hz. When the 10 000 m^2 coil is used, the early time segment of this curve is purposely saturated. It is common to collect data sets at two receiver polarities, various gain settings, base frequencies, and with receiver coils of different effective areas. These various data sets are combined in one transient-decay curve that is subsequently entered into inversion routines.

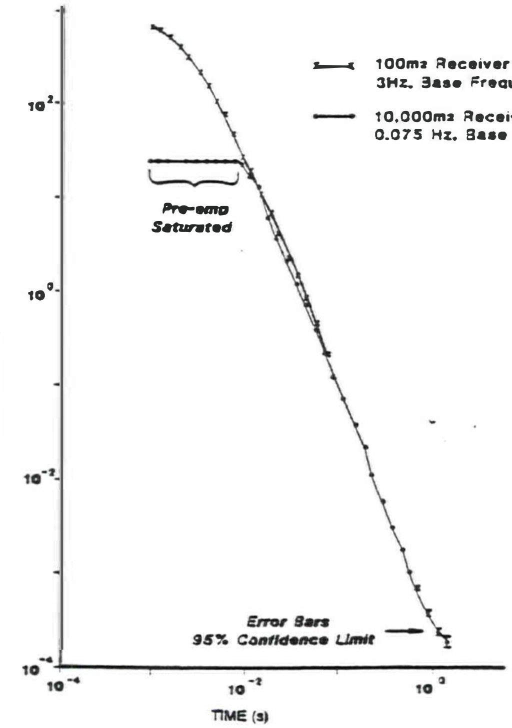

FIG. 6. Emf$_z$ measured in center of 500 m by 500 m transmitter loop.

Definition of Apparent Resistivity

All electrical and electromagnetic methods commonly transform the voltages or emf's measured into apparent resistivities. In TDEM several definitions of apparent resistivity are in use (Kaufman and Keller, 1983; Goldman, 1988) and the merits and pitfalls of the various definitions have been reviewed in Spies and Eggers (1986). These pitfalls are often avoided by (1) integrating inversions with available geologic data, and (2) using albums of forward-model curves for first-guess solutions. In all the case histories late-stage (Kaufman and Keller, 1983) apparent resistivity curves are used. Two reasons for that selection were (1) over a large range of time late-stage behavior is observed in central-loop soundings, and (2) extensive volumes of late-stage model curves (Goldman and Rabinovich, 1974) are available.

Data Interpretation

All the examples shown in the case histories were interpreted by one-dimensional (1-D) inversions of the data using a ridge-regression inversion program (ARRTI, Interpex Ltd, 1985). The input for the program are the emfs measured in various time gates, certain equipment and survey parameters (transmitter loop size, current, ramp time, receiver coil effective area), and number of layers to be used in the inversion. Also, an initial solution is entered. Goldman (1988) discussed the dependence of inversion routines on this first guess. To mitigate convergence to unrealistic solutions, first guesses are made to correspond with known geologic conditions, and depending on the quality of available geologic information, certain parameters in a geoelectric section may be fixed at specific values, e.g., as observed in borehole logs.

In TDEM soundings there is merit in carefully considering inversion errors at each time gate, because each section of the curve is often diagnostic of a certain depth section (Kaufman and Keller, 1983; Raiche and Gallagher, 1985). This can be illustrated by a central loop TDEM sounding with a 500 m by 500 m transmitter loop over a Tertiary valley fill in Nevada. Figure 7b shows the late-stage, apparent resistivity curve and Figure 7a two 1-D inversions for this sounding. The difference between the two inversions is the absence of a resistive layer (basalt flow) in section 1, and its presence in section 2. Figure 7c shows the error between the measured data and the two inversions. The increased error over the early time range suggested inserting an additional layer into the inversion. The existence of this resistive layer has been confirmed by drilling.

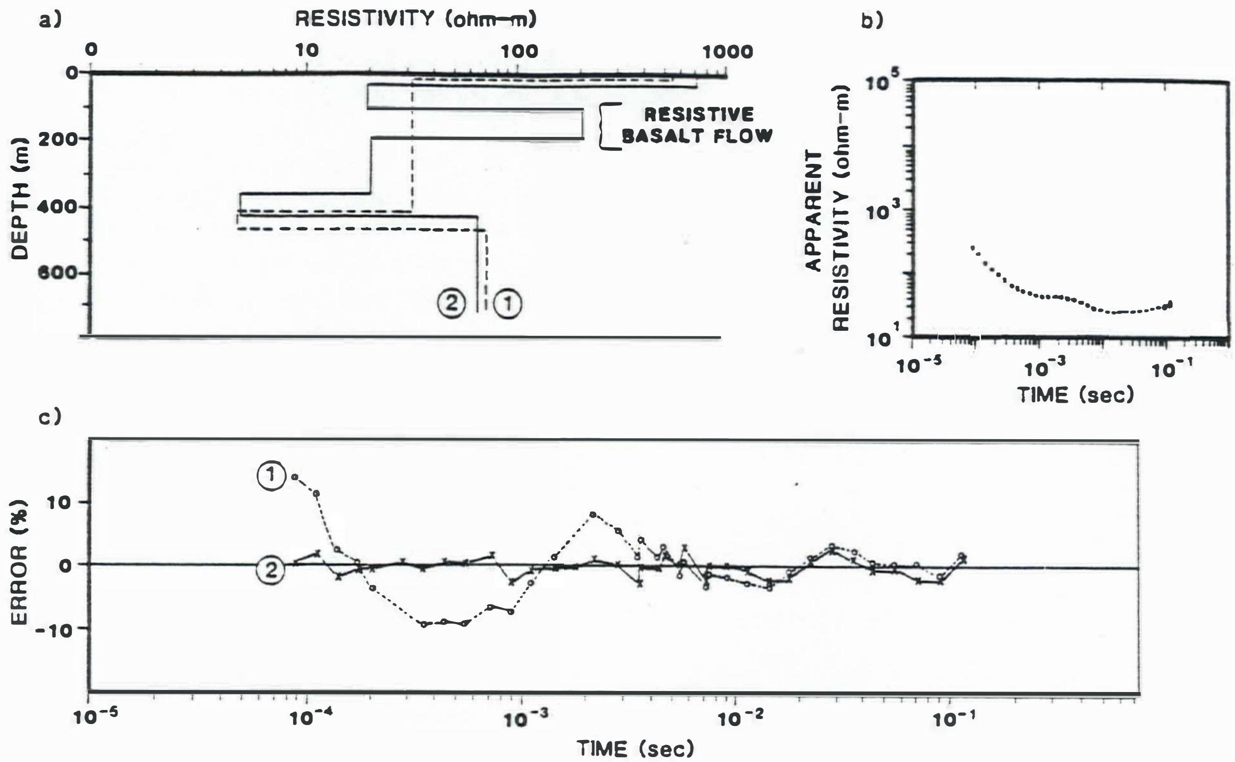

FIG. 7. Geoelectric sections (a) derived from 1-D inversions of measured apparent resistivity curve (b) over Tertiary Valley fill in Nevada. For each geoelectric section error of inversion is shown as function of time (c).

Validity of One-Dimensional Interpretation

The complexity of evaluating the influence of 2-D and 3-D structures of TDEM data is often cited as a disadvantage (Goldman, 1988). Indeed, currently, computations of 2-D and 3-D structures require computations that cannot be economically and practically applied in routine exploration programs. From the 2-D and 3-D computations (Newman et al., 1987) that have been published, important conclusions can be derived about the validity of 1-D interpretations in the presence of 2-D and 3-D structures. For example, Newman et al. (1987) computed the response over a resistive and conductive 3-D structure buried in a layered half-space at a depth of about 300 m. They reached the conclusion that 1-D inversions gave good estimates of the depth of burial of the 3-D structure, but unreliable depth extent and resistivities of the 3-D body. They used relatively large transmitter loops (1000 m by 1000 m) compared to exploration depth (1000 m) in their computations.

Drill-hole control is seldom sufficient to evaluate thoroughly the influence of 2-D and 3-D structures on a data set. Our experience, based on several thousand soundings with transmitter loop dimensions varying from 30 m by 30 m to 500 m by 500 m, is that 1-D interpretations yield good depth interpretations in the vast majority of work undertaken. Nevertheless, practical algorithms for data interpretation in the presence of 2-D and 3-D structures is an important need in TDEM soundings. Some efforts in that direction are promising (James, 1988).

Case Histories

Case History—High Level Nuclear Waste Repository Siting

The storage panels of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico are being mined in the bedded salts of the Salado formation at a depth of about 600 m below ground surface. Underlying the Salado formation is the Castile formation, which is composed primarily of anhydrite and halite. It is known from oil and gas drilling that the Bell Canyon formation, underlying the Castile formation, can contain brines (Barrows et al., 1982).

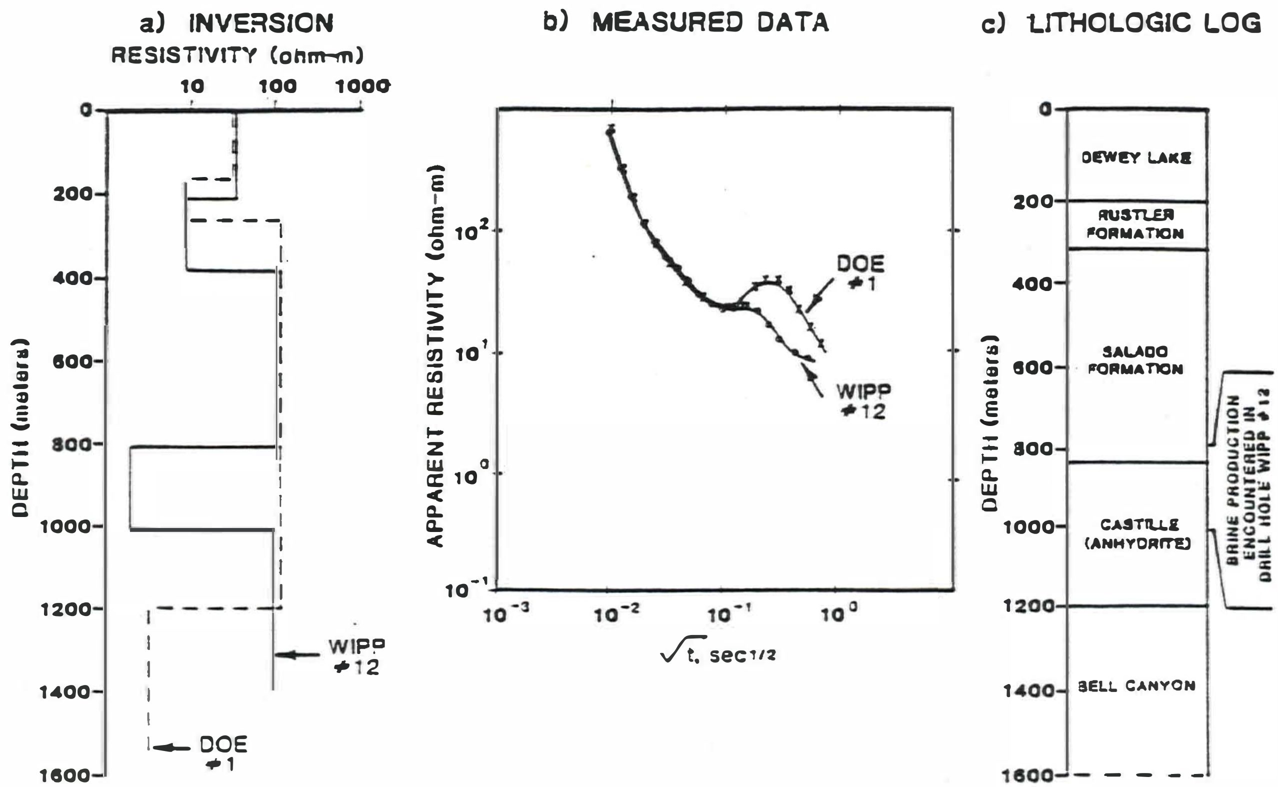

FIG. 8. Two measured late-stage apparent resistivity curves (b) and corresponding geoelectric sections derived from 1-D inversions (a). Also shown is a lithologic log common to both sounding locations (c).

The concept for placing a high level nuclear waste (HLW) repository in bedded salts at 600 m is to exploit the low hydraulic permeabilities of overlying bedded salts, and underlying anhydrites and halites. However, in the general vicinity of Carlsbad, New Mexico, drill holes encountered pressurized brine reservoirs at depths between 730 m and 915 m in the Castille formation (Register, 1981). The objective of TDEM surveys was to map the depth of first occurrence of brine over the waste storage panels and surrounding area.

A TDEM survey was conducted on a 500 m grid using central loop TDEM soundings over the waste storage panels and at selected drill hole locations. The transmitter loop dimensions employed were 500 m by 500 m and the TDEM equipment used was the Geonics EM-42.

Figure 8b shows two apparent resistivity curves located within 150 m of two drill hole locations, WIPP #12 and DOE #1. The resistivity layering derived from 1-D inversions for these two soundings is given in Figure 8a., and Figure 8c shows a lithologic log common to WIPP #12 and DOE #1. In the drilling of WIPP #12, brines were encountered at a depth of 850 m, and in drill hole DOE #1 no brines were encountered to total depth (TD = 900 m). The depth of first occurrence of brine observed in WIPP #12 is in excellent agreement with the depth of the low resistivity layer derived from the 1-D inversion of the adjacent TDEM sounding. Depth of occurrence of the low resistivity layer derived from the TDEM inversion near drill hole DOE #1 is at 1200 m, some 300 m below TD, and at a depth corresponding to the Bell Canyon formation.

The 1-D inversions of TDEM soundings over the waste storage panels showed first depth of occurrence of brine below 1050 m. This depth generally corresponds to the Bell Canyon formation. Thus, the 1-D interpretations of the depth of first occurrence of brine were consistent with available ground truth. A major concern remains the minimum dimensions of brine occurrences detectable with central loop soundings. This problem is being addressed by 2-D and 3-D forward modeling.

There are several other important objectives in environmental geophysics for mapping depth of first occurrences of brine, such as:

(1) Siting injection zones for oil field brines, and other liquid waste injection wells. Regulations require

injection zones to have a concentration of dissolved solids greater than 10 000 ppm and confining zones must separate US drinking water supplies (USDW) and injection zones (Federal Register, 1987).

(2) Monitoring migration of wastes upward from injection zones along fractures, abandoned wells, or faulty casings (Fitterman et al., 1986).

Mapping Encroachment of Salt Water Into Fresh-Water Aquifers

Intrusion of salt water in coastal aquifers often has as its main cause excessive withdrawal of ground water. It has long been recognized that surface electrical or electromagnetic methods can be effective in mapping fresh water—salt water interfaces (Flathe, 1964). Here, the application of TDEM surveys for this purpose is illustrated by a case history from the Salinas Valley, CA (Mills et al., 1988). A schematic hydrogeologic cross-section of the study area is given in Figure 9. There are four aquifer zones (1) a perched aquifer in which the ground water is heavily contaminated by fertilization, (2) a 180 ft aquifer approximately 60 m thick in which salt water has intruded under about 15 000 acres, (3) a 400 ft aquifer in which salt-water intrusion has been observed under about 6600 acres, and (4) a 900 ft aquifer in which no salt-water intrusion has yet been observed.

Thus, salt-water intrusion has progressed farthest inland into the 180 ft aquifer, so that to map water quality in the 400 ft aquifer requires exploration through a 180 ft aquifer containing high concentrations of dissolved solids. This information was used in designing the survey. To map salt-water encroachment in the 180 ft aquifer 100 m by 100 m transmitting loops were em-

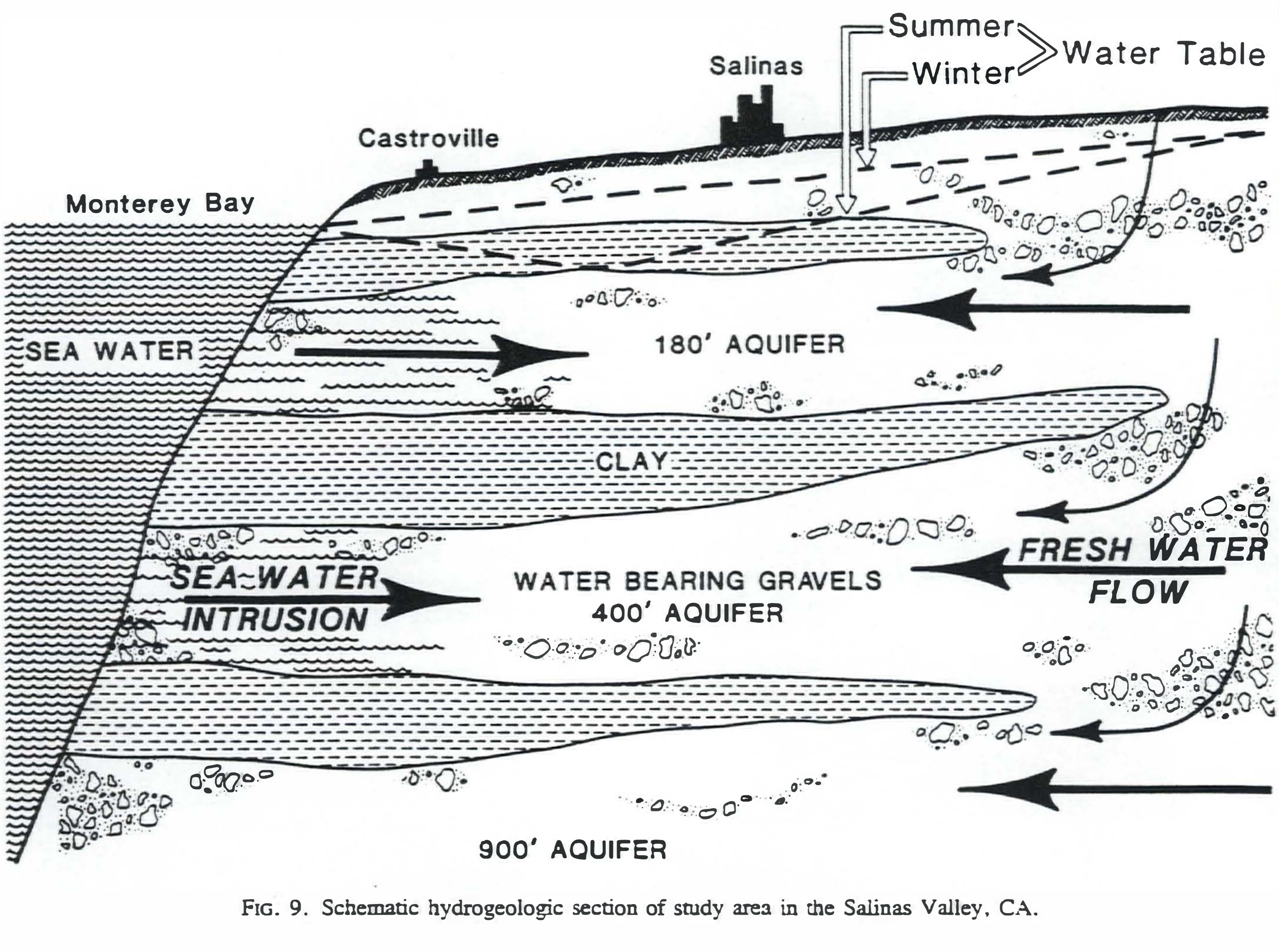

FIG. 9. Schematic hydrogeologic section of study area in the Salinas Valley, CA.

ployed. These transmitting loop dimensions provided sufficient field strength to derive the resistivity variation in the 180 ft aquifer. Larger transmitting loop dimensions (200 m by 200 m) were employed for exploration in the 400 ft aquifer. Approximately 100 stations were measured.

A series of four late-stage apparent-resistivity curves along cross-section B-B′ (Figure 12) are shown on Figure 10 along with geoelectric sections derived from 1-D inversions. Figure 11 shows the geoelectric section derived from TDEM soundings along profile B-B′. In the 180 ft aquifer the resistivity gradually increases inland from 1.5 $\Omega \cdot m$ (station L24/3) to 18 $\Omega \cdot m$ (station L10/1). In the 400-ft aquifer the resistivity increased from 6.0 $\Omega \cdot m$ to in excess of 20 $\Omega \cdot m$.

Information from monitoring wells maintained by the Monterey County Flood Control and Water Conservation District was used to help constrain the number of layers used for the inversions of the TDEM data, and to correlate formation resistivities with equivalent chloride concentration. Correlation of formation resistivities with chloride concentration showed that a resistivity of approximately 8 $\Omega \cdot m$ corresponds to a 500 ppm chloride concentration. Figure 12 shows the surface projection of the 500 ppm isochlor contours (8 $\Omega \cdot m$ formation resistivity) in the 180 ft and 400 ft aquifers. The 500 ppm isochlor, based on monitoring wells, is also shown. There is more detail in the contours derived from the TDEM surveys mainly because of the higher station density.

These types of TDEM surveys have now been performed in several areas of Florida (Steward and Gay, 1981), Massachusetts (Fitterman and Hoekstra, 1982), California (Mills et al., 1988), and New York. Important advantages of TDEM soundings in these surveys are:

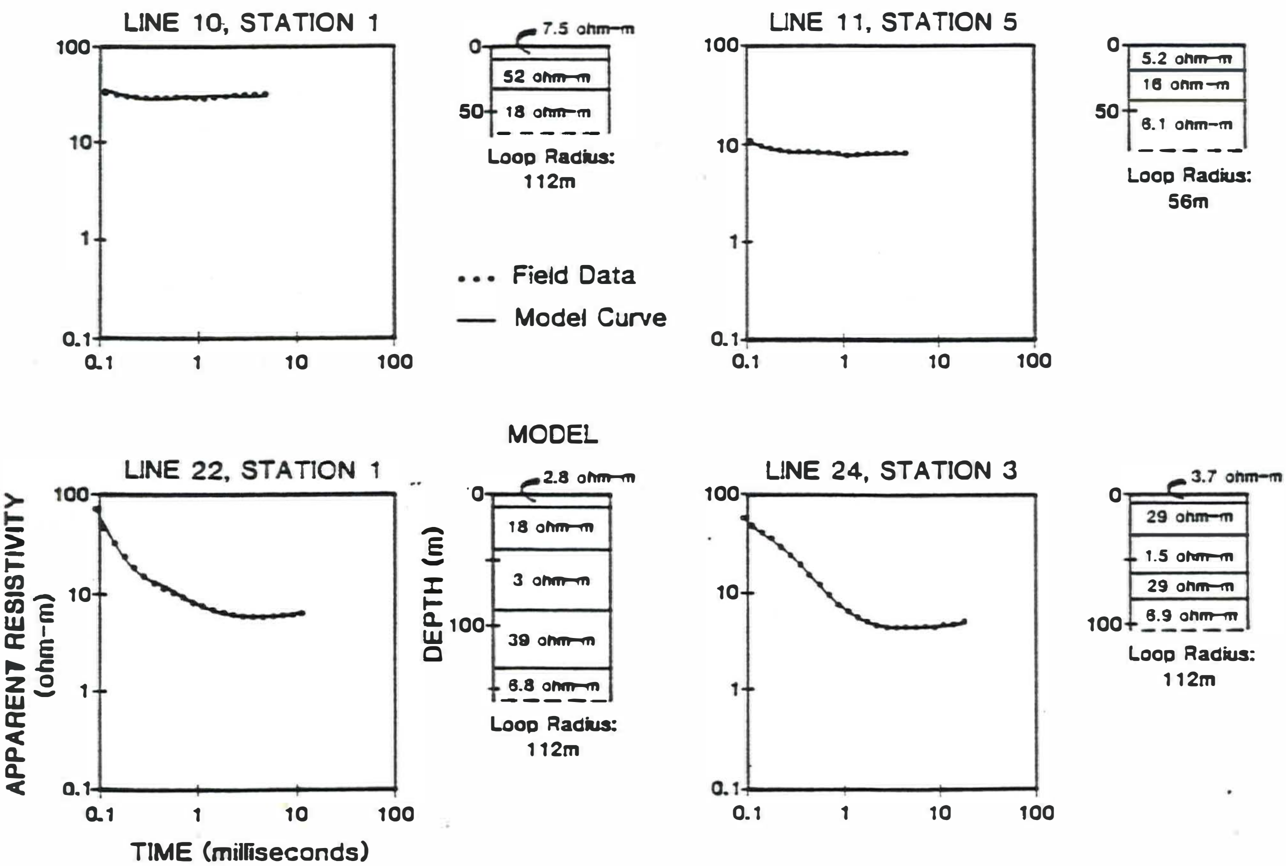

FIG. 10. Four apparent resistivity curves and inverted geoelectric sections along section B-B′ (Figure 12).

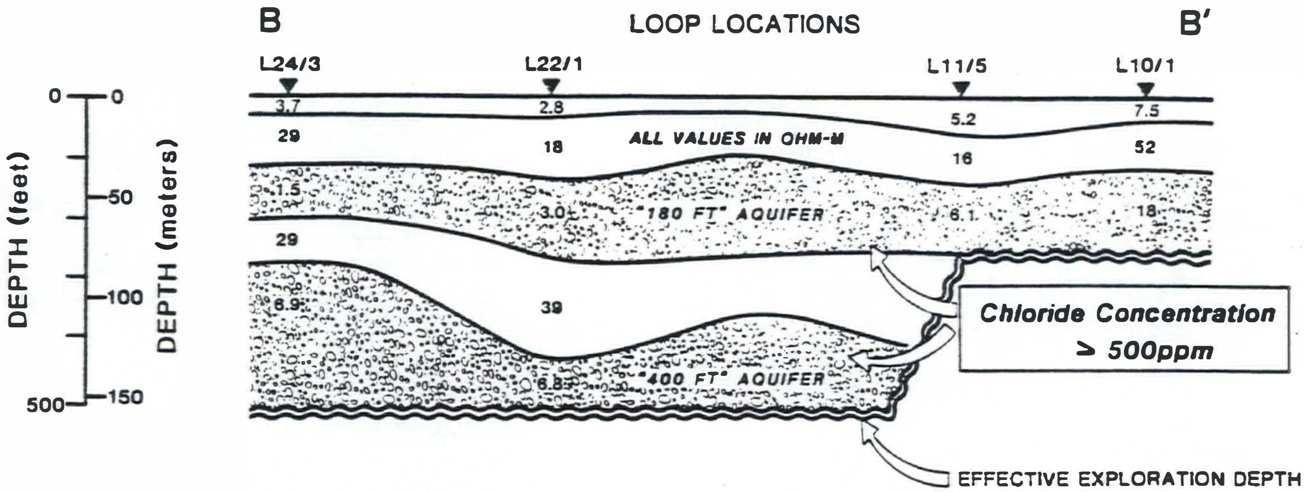

FIG. 11. Geoelectric section B-B' derived from TDEM soundings.

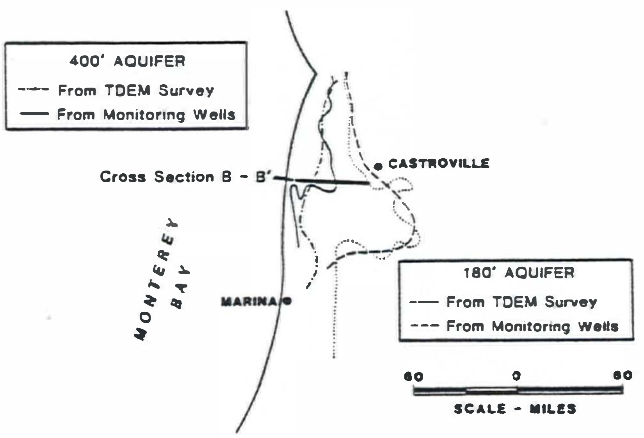

FIG. 12. Comparison of position of 500 ppm isochlor in 180 ft and 400 ft aquifers derived from monitoring wells and TDEM soundings.

(1) Coastal areas are often urbanized and limited space is available for measurements. TDEM measurements were often made in available open spaces such as high school athletic fields and parks.

(2) Ambient electrical noise (e.g., powerlines and radio stations) is high in developed areas. The signal stacking used in TDEM has proven an effective way for recovering signal from noise.

The utility of TDEM surveys for water management plans are in (1) providing optimum location for placement of monitoring and production wells, (2) determining depth of completion of such wells, (3) interpolating the position of the fresh water–saline water interface between wells, and (4) monitoring the movement of the interface over time. Geophysical stations can be moved from year to year, while monitoring wells lose some of their usefulness once the fresh water–saline water interface has migrated past their locations.

Shallow TDEM Surveys

Important exploration objectives for shallow (< 50 m) electrical exploration in environmental geophysics are

mapping continuity of confining layers, such as clay lenses;

mapping the presence of contaminants (e.g., originating from brine ponds) and pathways for migration of contaminants, such as fractures and shear zones;

correlating hydraulic transmissivities to electrical conductance (e.g., Huntley, 1986).

The geophysical methodologies applied to these exploration problems have mainly been dc resistivity soundings (e.g., Evans et al., 1982) and frequency-domain electromagnetic conductivity profiling (e.g., McNeill, 1982). With the recent availability of a TDEM system (Geonics EM-47) for shallow exploration, some of these objectives are now within the exploration depth range of TDEM. An example of shallow central-loop soundings with a prototype EM-47 is a survey over relatively thin basalt flows near Golden, Colorado.

On North and South Table Mountain in Golden, Colorado, lava flows overlie the Denver formation. Figure 13a shows the geologic section of the upper 100 m on North Table Mountain (Waldschmidt, 1939). Figure 13c shows an apparent resistivity curve measured in the center of a 30 m by 30 m transmitter loop with the EM-47 and its 1-D inversion. A peak current of 2 A was driven through the loop, and the ramp turn-off (Figure 4a) was 2.5 μs. The first time gate was centered at 6.4 μs and data were collected at base frequencies of 300 Hz and 30 Hz. The geoelectric section derived from the 1-D inversion (Figure 13b) shows good agreement between geologic boundaries and breaks in resistivity.

For this geoelectric section and for 30 m by 30 m transmitter loops (R = 15 m), late stage commences at about 10^{-5} s (Figure 3), so that almost the entire measured curve is in late-stage. Also shown on Figure 13c are forward modeled curves with different thicknesses of the upper basalt flow, while all other parameters were held constant. Large changes in the curves occur mainly

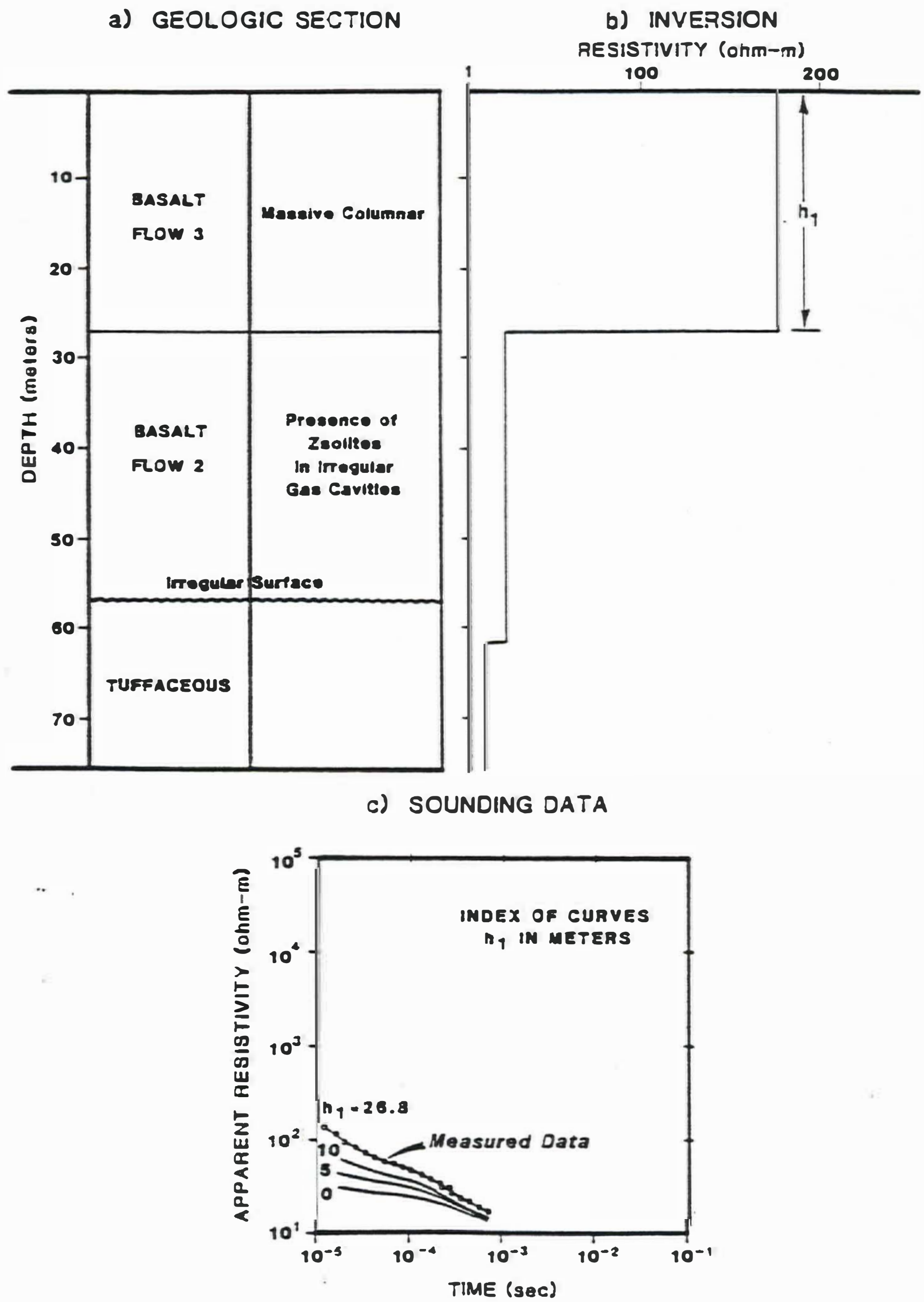

FIG. 13. (a) Geologic section of North Table Mountain, Golden, CO; (b); and geoelectric section derived from 1-D inversion of central loop sounding data with 30 m by 30 m transmitter loop; (c) the measured apparent resistivities are superimposed on a series of forward model curves in which the thickness of the upper basalt layer is varied.

over the time range from 10^{-5} s to 10^{-3} s; the time range covered by EM-47 measurements.

The conclusions from a number of conducted surveys is that the EM-47 can be employed in the depth range from 5 m to 75 m, depending somewhat on the geoelectric section. Since transmitter loop dimensions of 30 m by 30 m can be employed, survey productivity is high (30 to 50 stations per day). The TDEM EM-47 promises to be an effective methodology for electrical mapping in environmental geophysics, particularly in urban areas where space is limited and ambient noise is high.

Discussion

Focusing on the use of TDEM methods in environmental geophysics is such a narrow focus that there is a danger of overstating the utility of TDEM, compared to other electrical and electromagnetic measurement techniques. Raiche et al. (1985) and Fitterman et al. (1988) show that the range of equivalence in some geoelectric sections can in principle be reduced by combined use of dc resistivity and TDEM soundings. It is, therefore, important to note that the exploration objective in all three case histories consisted of determining depth to a conductive stratum, objectives optimally suited for electromagnetic techniques. TDEM surveys and other electromagnetic techniques have limitations for detecting thin resistive strata, and such limitations are readily evaluated by forward modeling.

One advantage of TDEM not evident from forward modeling computations is the absence of scatter in the data. The data scatter frequently observed in dc resistivity soundings, and distant source techniques (controlled source audiomagnetotelluric, audiomagnetotelluric, and magnetotelluric methods) are often due to lateral variation in resistivity and measurement of the electric field. The scatter is reduced in central loop TDEM soundings mainly because of the short source/receiver separation and measurement of the time derivative of magnetic fields. The apparent resistivity curves shown in these investigations are typical of a large number of stations. No smoothing of the data is performed before inversions.

The recent availability of a shallow TDEM system for the exploration depth range from 5 m to 75 m makes this technique suitable for such environmental studies as well-site protection programs, and mapping plumes of ground-water contamination. Contamination plumes are often confined to narrow zones, and the high lateral resolution possible with shallow central loop TDEM soundings allows definition of both the lateral and vertical extent of such plumes.

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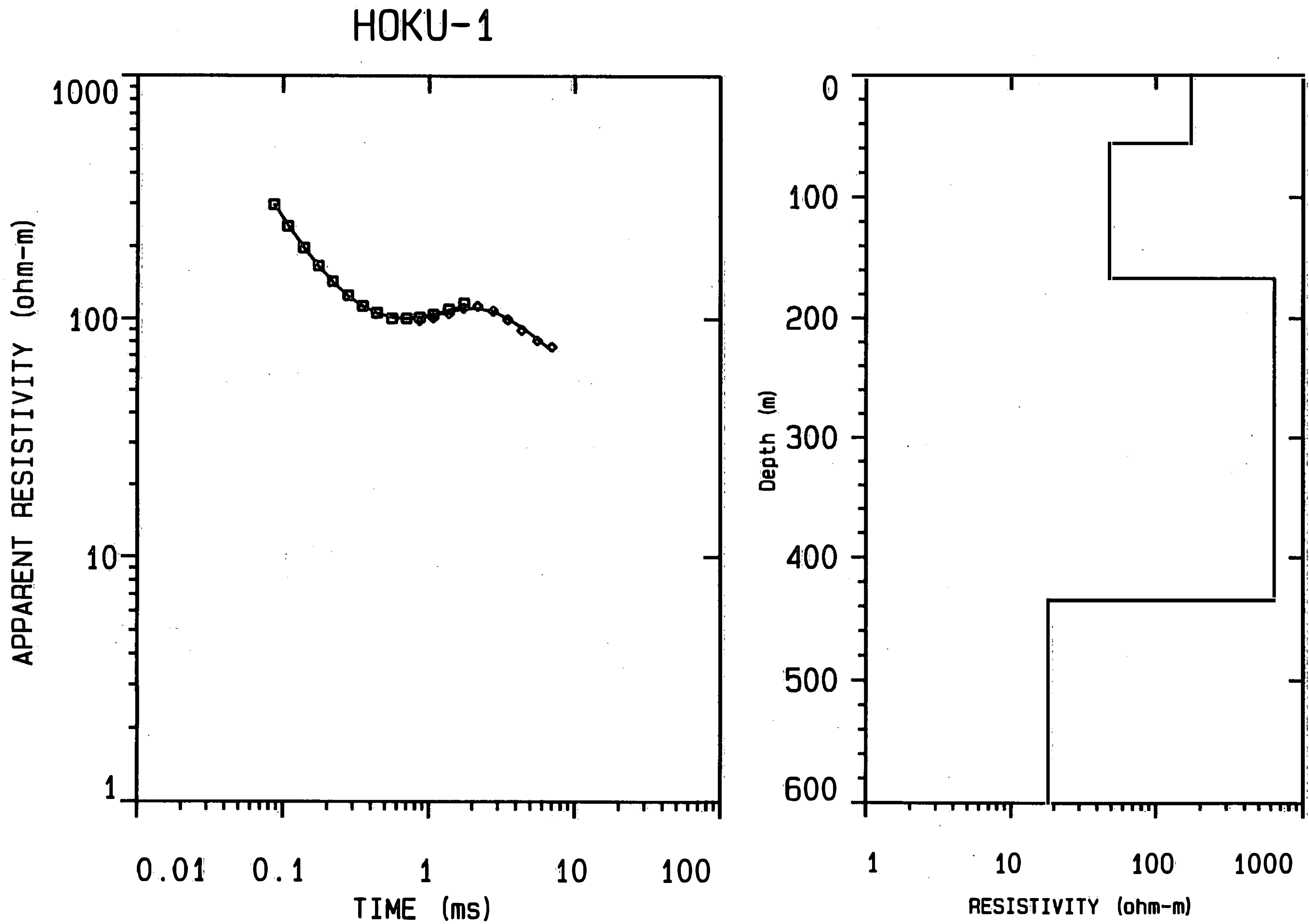


HOKU-1
1000
100
10
1
APPARENT RESISTIVITY (ohm-m)
0.01
0.1
1
10
100
TIME (ms)
0
100
200
300
400
500
600
Depth (m)
1
10
100
1000
RESISTIVITY (ohm-m)

DATA SET: HOKU-1

CLIENT: PUU O HOKU RANCH DATE: 12-05-98
LOCATION: MOLOKAI, HAWAII SOUNDING: 1
COUNTY: MAUI ELEVATION: 290.00 m
PROJECT: PUU O HOKU RANCH EQUIPMENT: Geonics PROTEM
LOOP SIZE: 244.000 m by 244.000 m AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y) TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 100.0000 N: 1.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 2.203 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			290.0	951.4	
1	174.6	55.96	234.0	767.7	0.320
2	48.34	110.8	123.1	403.9	2.29
3	635.9	268.2	-145.0	-475.7	0.421
4	18.32				

ALL PARAMETERS ARE FREE

CURRENT: 18.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 4 RAMP TIME: 160.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	47288.4	47101.1	0.396
2	0.108	37090.5	36834.7	0.689
3	0.138	27421.3	27318.5	0.374
4	0.175	19610.8	19816.5	-1.04
5	0.218	14093.6	14257.1	-1.15
6	0.278	9397.5	9493.5	-1.02
7	0.351	6118.2	6149.3	-0.508
8	0.438	3887.7	3905.1	-0.448
9	0.558	2296.4	2269.1	1.18
10	0.702	1296.9	1300.6	-0.285
11	0.858	773.8	775.9	-0.273
12	1.06	431.2	432.6	-0.313
13	1.37	213.6	216.6	-1.40

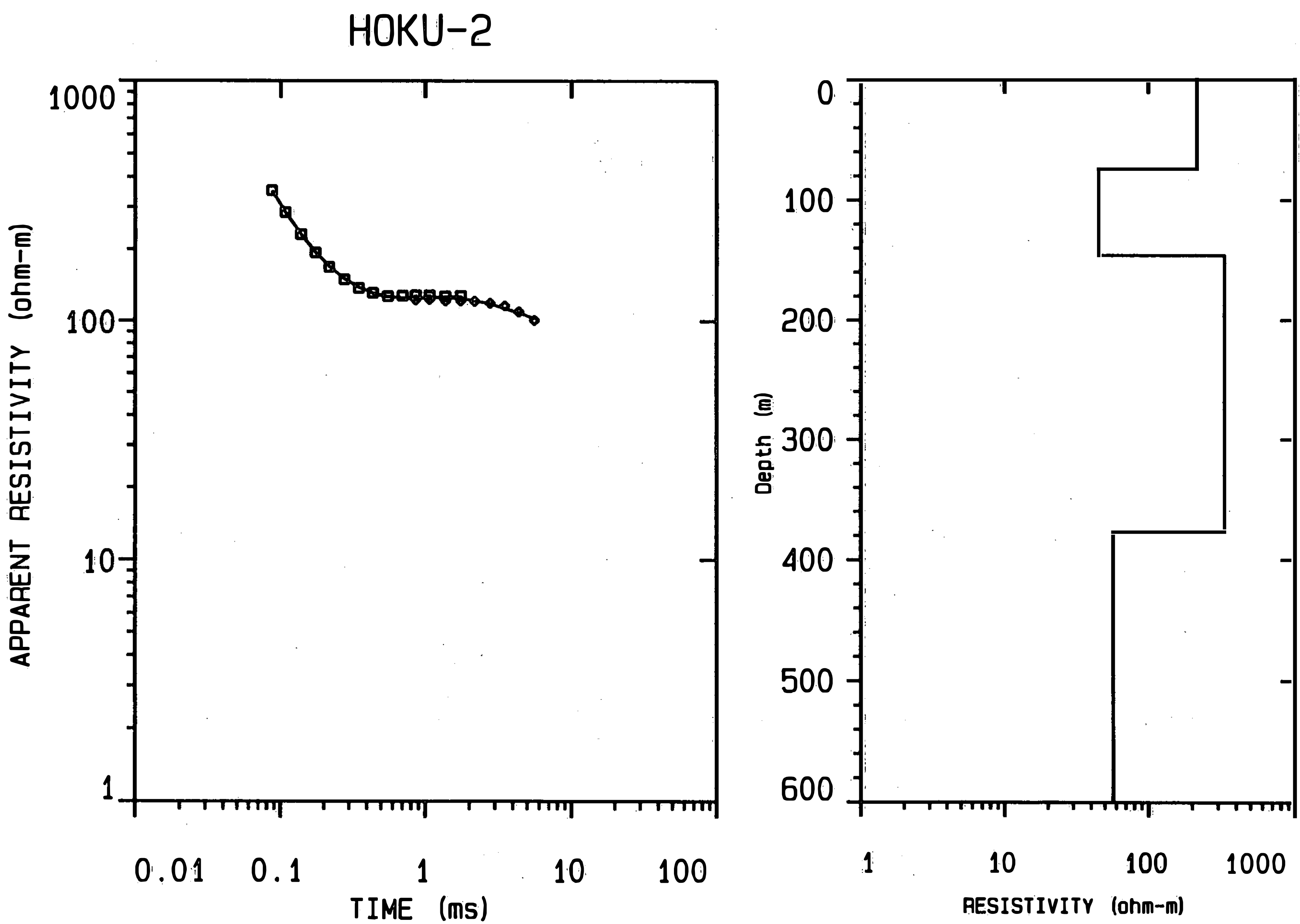
No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	1.74	107.6	112.3	-4.37

CURRENT: 18.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 160.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	0.857	809.7	783.0	3.29
16	1.06	450.8	437.1	3.03
17	1.37	227.1	220.9	2.72
18	1.74	115.0	116.3	-1.13
19	2.17	64.71	66.72	-3.09
20	2.77	37.66	37.84	-0.475
21	3.50	23.72	23.40	1.34
22	4.37	15.92	15.27	4.08
23	5.56	10.16	9.92	2.41
24	6.98	6.29	6.60	-4.91

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.22						
P 2	0.04	0.88					
P 3	0.01	-0.01	0.01				
P 4	-0.04	0.08	-0.03	0.49			
T 1	0.29	0.10	0.00	-0.05	0.76		
T 2	-0.07	-0.16	-0.07	0.14	0.19	0.74	
T 3	-0.02	0.01	0.06	0.07	0.00	0.01	0.97
	P 1	P 2	P 3	P 4	T 1	T 2	T 3


HOKU-2
APPARENT RESISTIVITY (ohm-m)
1000
100
10
1
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
600
1
10
100
1000
RESISTIVITY (ohm-m)

DATA SET: HOKU-2

CLIENT: PUU O HOKU RANCH
LOCATION: MOLOKAI, HAWAII
COUNTY: MAUI
PROJECT: PUU O HOKU RANCH
LOOP SIZE: 244.000 m by 244.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: E: 100.0000 N: 2.0000

DATE: 12-06-98
SOUNDING: 2
ELEVATION: 323.00 m
EQUIPMENT: Geonics PROTEM
AZIMUTH:
TIME CONSTANT: NONE
SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 2.215 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			323.0	1059.7	
1	218.1	74.01	248.9	816.6	0.339
2	45.21	72.09	176.8	580.0	1.59
3	334.6	230.5	-53.70	-176.2	0.689
4	57.07				

ALL PARAMETERS ARE FREE

CURRENT: 18.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 4 RAMP TIME: 155.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	36969.3	37300.8	-0.896
2	0.108	29149.0	29320.8	-0.589
3	0.138	21725.5	21652.7	0.335
4	0.175	15556.5	15502.9	0.344
5	0.218	11078.4	10951.2	1.14
6	0.278	7233.3	7126.9	1.47
7	0.351	4566.3	4516.2	1.09
8	0.438	2814.8	2820.8	-0.210
9	0.558	1615.8	1622.9	-0.437
10	0.702	902.1	932.0	-3.32
11	0.858	544.1	565.5	-3.93
12	1.06	316.6	325.2	-2.72
13	1.37	170.7	172.6	-1.11

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	1.74	93.56	94.70	-1.21

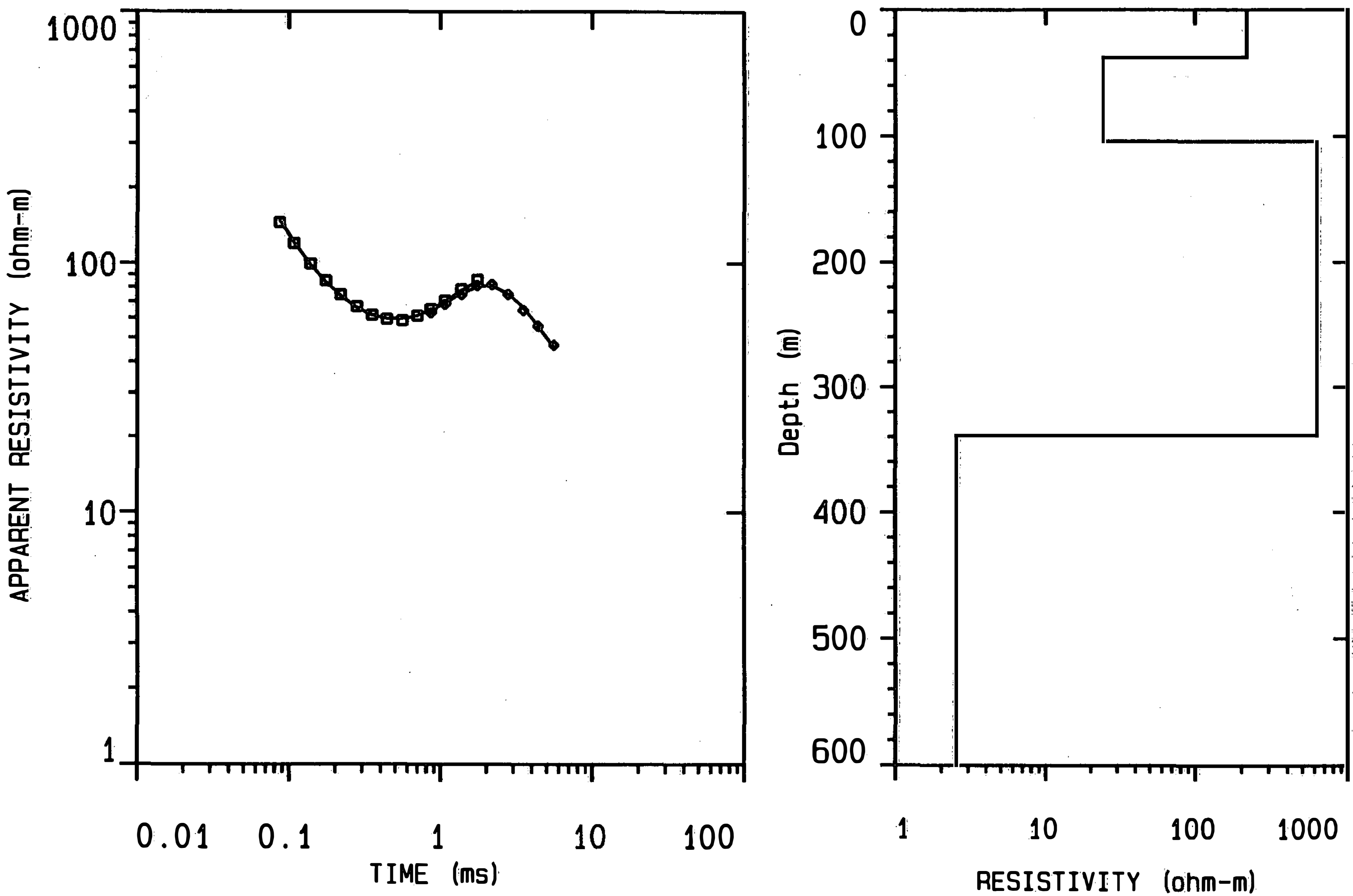
CURRENT: 18.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 155.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	0.857	582.0	569.9	2.07
16	1.06	334.9	327.8	2.12
17	1.37	182.9	175.0	4.30
18	1.74	100.4	96.93	3.51
19	2.17	58.29	57.79	0.860
20	2.77	32.46	32.70	-0.734
21	3.50	18.81	19.59	-4.14
22	4.37	11.77	11.93	-1.37
23	5.56	7.31	7.10	2.74

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	P 3	P 4	T 1	T 2	T 3
P 1	0.15						
P 2	0.09	0.74					
P 3	0.04	0.00	0.12				
P 4	-0.05	0.06	-0.05	0.71			
T 1	0.25	0.11	-0.03	-0.01	0.84		
T 2	-0.06	-0.32	-0.14	0.10	0.19	0.53	
T 3	0.00	-0.02	0.21	0.17	0.01	-0.02	0.84

HOKU-3



1000
100
10
1
APPARENT RESISTIVITY (ohm-m)
0.01
0.1
1
10
100
TIME (ms)
0
100
200
300
400
500
600
Depth (m)
1
10
100
1000
RESISTIVITY (ohm-m)

DATA SET: HOKU-3

CLIENT: PUU O HOKU RANCH
LOCATION: MOLOKAI, HAWAII
COUNTY: MAUI
PROJECT: PUU O HOKU RANCH
LOOP SIZE: 182.000 m by 182.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: E: 100.0000 N: 3.0000

DATE: 12-06-98
SOUNDING: 3
ELEVATION: 224.00 m
EQUIPMENT: Geonics PROTEM
AZIMUTH:
TIME CONSTANT: NONE
SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 2.028 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			224.0	734.9	
1	218.4	37.63	186.3	611.2	0.172
2	24.26	66.35	120.0	393.7	2.73
3	623.7	234.7	-114.7	-376.3	0.376
4	2.51				

ALL PARAMETERS ARE FREE

CURRENT: 17.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 4 RAMP TIME: 115.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	72800.2	70587.2	3.03
2	0.108	56006.8	55422.6	1.04
3	0.138	40374.9	40723.5	-0.863
4	0.175	28117.3	28892.8	-2.75
5	0.218	19696.8	20160.5	-2.35
6	0.278	12710.8	12873.4	-1.27
7	0.351	7966.4	7962.3	0.0511
8	0.438	4845.0	4812.5	0.671
9	0.558	2703.3	2634.5	2.54
10	0.702	1420.7	1416.8	0.273
11	0.858	787.5	793.3	-0.738
12	1.06	404.2	411.5	-1.79
13	1.37	184.8	187.9	-1.64

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	1.74	89.13	91.17	-2.29

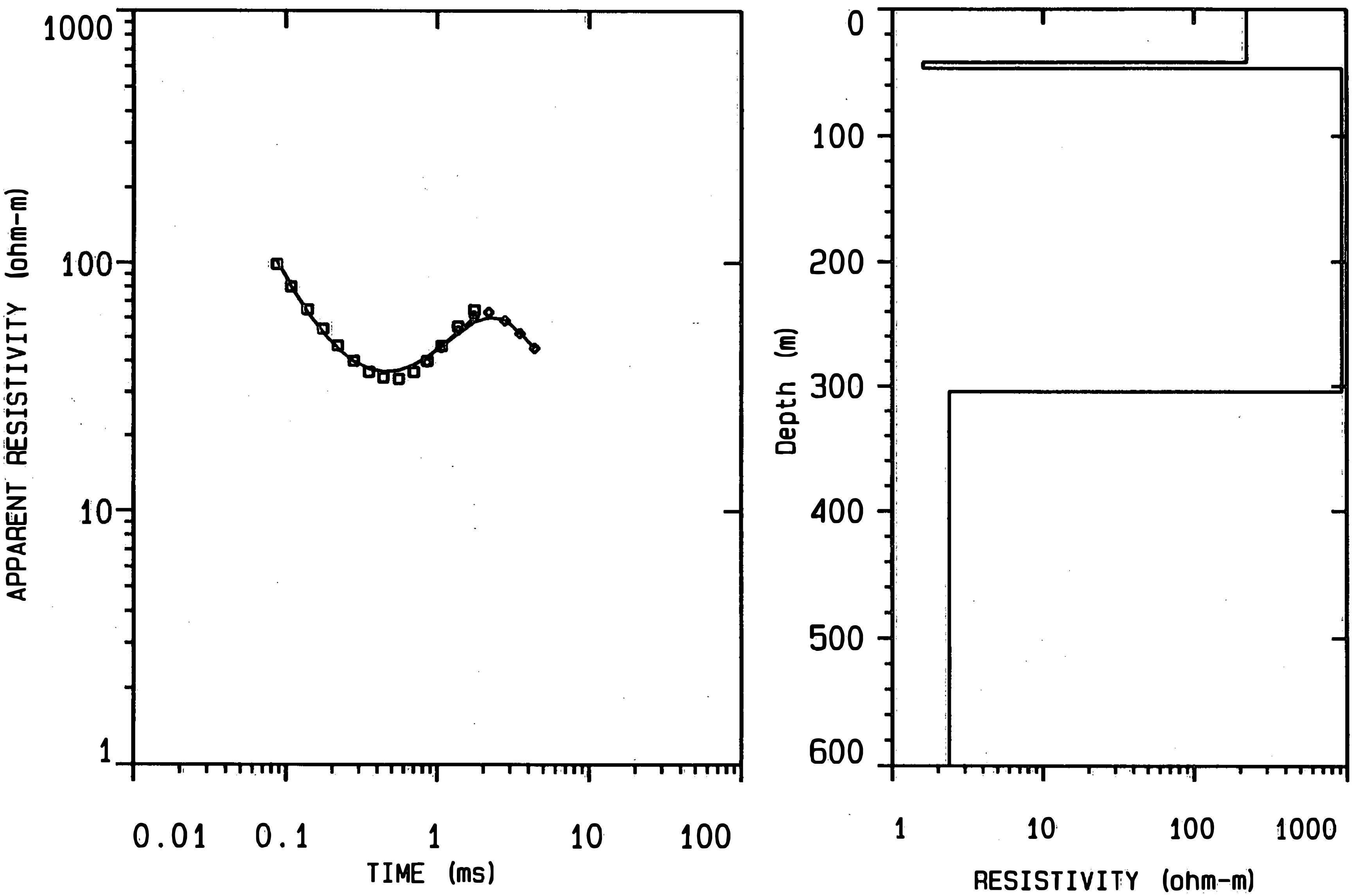
CURRENT: 17.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 115.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	0.857	830.2	803.8	3.17
16	1.06	427.2	419.0	1.91
17	1.37	198.7	195.1	1.80
18	1.74	96.35	98.09	-1.79
19	2.17	54.67	55.37	-1.29
20	2.77	34.18	33.79	1.16
21	3.50	23.80	22.88	3.87
22	4.37	17.05	17.03	0.115
23	5.56	12.14	12.51	-3.01

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.07						
P 2	0.00	0.83					
P 3	0.00	-0.01	0.01				
P 4	-0.02	0.10	-0.02	0.19			
T 1	0.12	0.15	0.00	-0.07	0.83		
T 2	-0.05	-0.20	-0.05	0.16	0.18	0.74	
T 3	-0.01	0.02	0.02	-0.06	-0.02	0.03	0.99
	P 1	P 2	P 3	P 4	T 1	T 2	T 3

HOKU-4



APPARENT RESISTIVITY (ohm-m)
1000
100
10
1
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
600
1
10
100
1000
RESISTIVITY (ohm-m)

DATA SET: HOKU-4

CLIENT: PUU O HOKU RANCH
LOCATION: MOLOKAI, HAWAII
COUNTY: MAUI
PROJECT: PUU O HOKU RANCH
LOOP SIZE: 182.000 m by 182.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: E: 100.0000 N: 4.0000 SLOPE: NONE

DATE: 12-07-98
SOUNDING: 4
ELEVATION: 205.00 m
EQUIPMENT: Geonics PROTEM
AZIMUTH:
TIME CONSTANT: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 6.347 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			205.0	672.6	
1	220.8	42.19	162.8	534.1	0.191
2	1.59	4.62	158.1	518.7	2.90
3	930.3	257.5	-99.32	325.8	0.276
4	2.36				

ALL PARAMETERS ARE FREE

CURRENT: 16.50 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 3 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	126823.0	120025.4	5.35
2	0.108	99805.3	99789.6	0.0156
3	0.138	74521.1	77389.9	-3.84
4	0.175	54010.1	57256.5	-6.01
5	0.218	39367.0	41077.0	-4.34
6	0.278	26559.4	26694.5	-0.508
7	0.351	17288.2	16546.0	4.29
8	0.438	10762.3	9909.8	7.92
9	0.558	6004.0	5307.0	11.60
10	0.702	3054.2	2771.3	9.26
11	0.858	1593.7	1507.1	5.43
12	1.06	748.3	749.6	-0.165
13	1.37	303.9	327.3	-7.67

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	1.74	132.9	147.9	-11.33

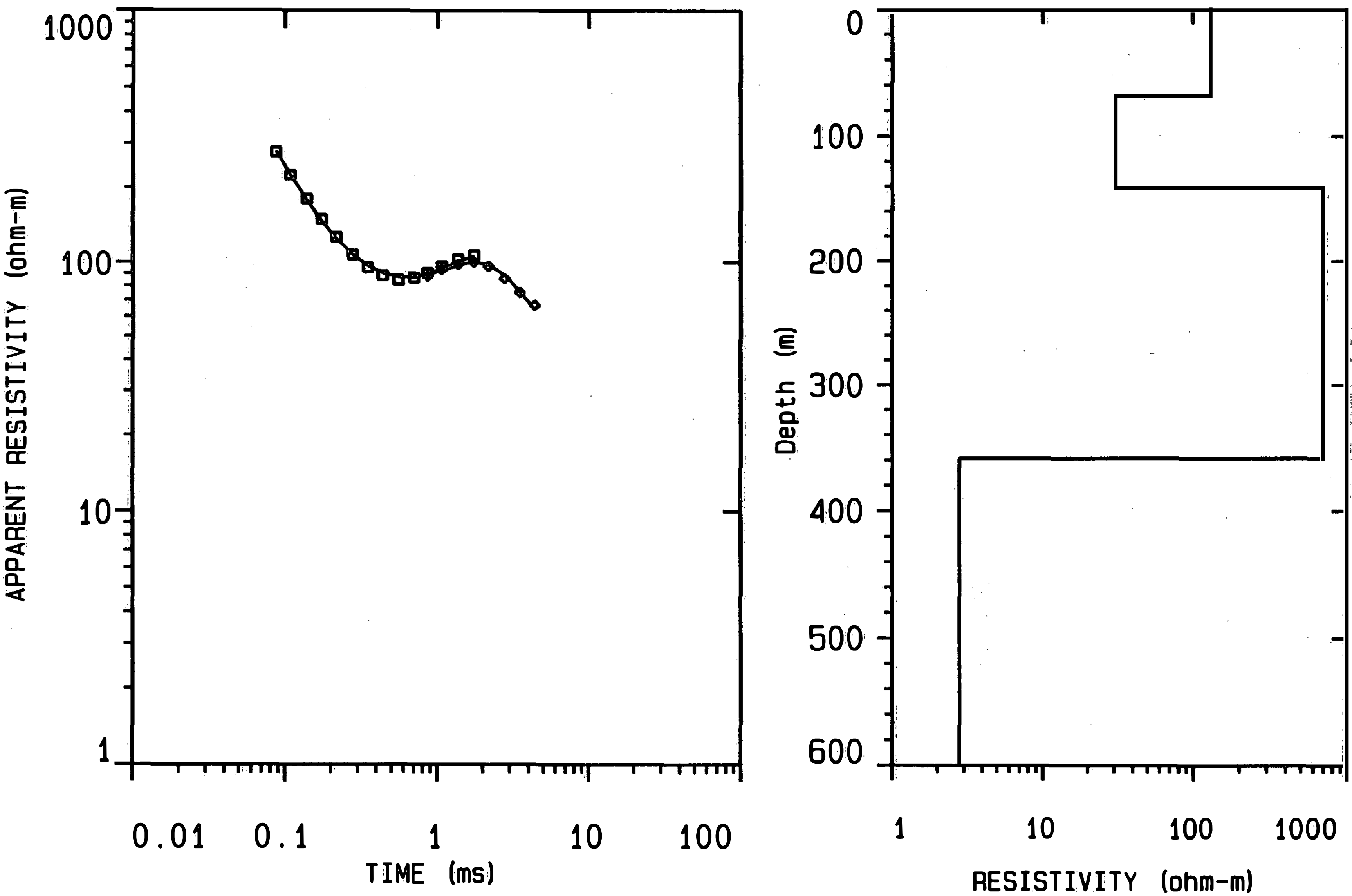
CURRENT: 16.50 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	0.857	1625.9	1522.8	6.33
16	1.06	768.4	759.4	1.16
17	1.37	321.4	336.7	-4.77
18	1.74	143.9	156.9	-9.01
19	2.17	79.05	85.14	-7.71
20	2.77	48.25	47.35	1.86
21	3.50	32.29	31.94	1.09
22	4.37	22.79	22.63	0.672

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	P 3	P 4	T 1	T 2	T 3
P 1	0.02						
P 2	0.01	0.59					
P 3	0.00	0.00	0.00				
P 4	-0.01	0.08	-0.02	0.11			
T 1	0.04	0.06	-0.01	0.01	0.97		
T 2	-0.04	-0.41	-0.03	0.11	0.06	0.59	
T 3	-0.01	-0.03	0.01	-0.02	0.01	-0.03	0.98

HOKU-5



1000
100
10
1
APPARENT RESISTIVITY (ohm-m)
0.01
0.1
1
10
100
TIME (ms)
0
100
200
300
400
500
600
Depth (m)
1
10
100
1000
RESISTIVITY (ohm-m)

DATA SET: HOKU-5

CLIENT: PUU O HOKU RANCH
LOCATION: MOLOKAI, HAWAII
COUNTY: MAUI
PROJECT: PUU O HOKU RANCH
DATE: 12-07-98
SOUNDING: 5
ELEVATION: 262.00 m
EQUIPMENT: Geonics PROTEM
LOOP SIZE: 244.000 m by 244.000 m
AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y)
TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 100.0000 N: 5.0000
SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 2.813 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			262.0	859.6	
1	131.1	68.19	193.8	635.8	0.519
2	30.95	72.90	120.9	396.6	2.35
3	704.2	217.5	-96.62	-316.9	0.308
4	2.80				

ALL PARAMETERS ARE FREE

CURRENT: 18.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 4 RAMP TIME: 160.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	52869.8	52336.8	1.00
2	0.108	41900.3	41992.3	-0.219
3	0.138	31556.6	32072.4	-1.63
4	0.175	23172.6	23897.6	-3.12
5	0.218	17198.2	17529.4	-1.92
6	0.278	11880.3	11860.0	0.170
7	0.351	7965.4	7747.7	2.73
8	0.438	5112.4	4927.7	3.61
9	0.558	2983.7	2840.3	4.80
10	0.702	1615.5	1603.2	0.761
11	0.858	916.4	933.3	-1.84
12	1.06	485.0	504.1	-3.94
13	1.37	235.3	242.7	-3.15

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	1.74	122.6	123.1	-0.436

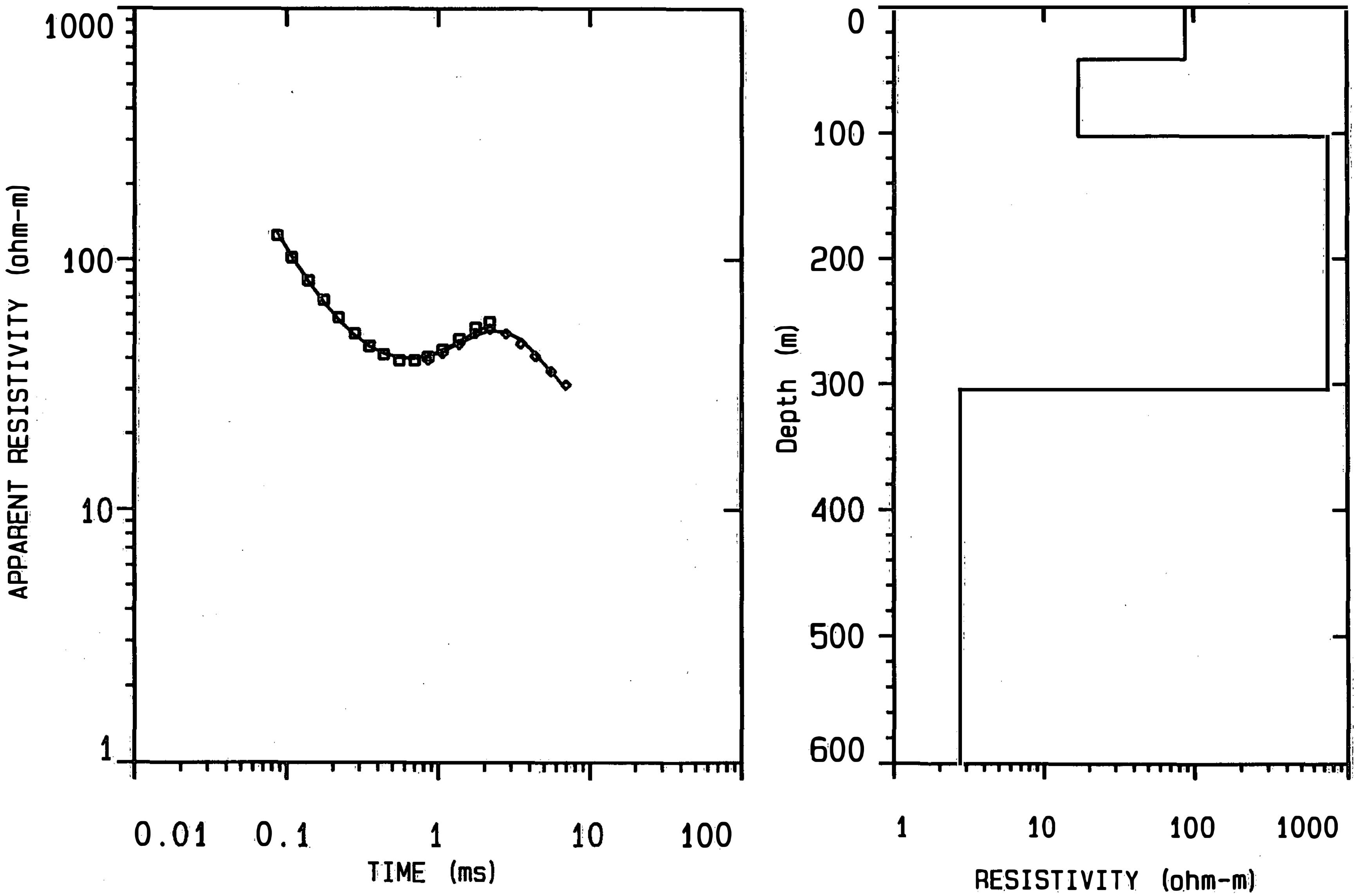
CURRENT: 18.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 6 RAMP TIME: 160.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	0.857	960.9	948.7	1.26
16	1.06	507.9	516.1	-1.60
17	1.37	252.5	254.2	-0.668
18	1.74	134.8	134.1	0.570
19	2.17	82.19	80.40	2.17
20	2.77	53.03	50.30	5.14
21	3.50	36.07	35.52	1.54
22	4.37	24.80	26.38	-6.37

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.35						
P 2	0.00	0.81					
P 3	0.01	0.00	0.00				
P 4	-0.03	0.09	-0.02	0.21			
T 1	0.28	0.10	-0.01	-0.03	0.81		
T 2	-0.14	-0.25	-0.04	0.18	0.20	0.63	
T 3	-0.04	0.04	0.02	-0.10	0.00	0.05	0.97
	P 1	P 2	P 3	P 4	T 1	T 2	T 3

HOKU-6


APPARENT RESISTIVITY (ohm-m)
1000
100
10
1
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
600
1
10
100
1000
RESISTIVITY (ohm-m)

DATA SET: HOKU-6

CLIENT: PUU O HOKU RANCH
LOCATION: MOLOKAI, HAWAII
COUNTY: MAUI
PROJECT: PUU O HOKU RANCH
DATE: 12-07-98
SOUNDING: 6
ELEVATION: 204.00 m
EQUIPMENT: Geonics PROTEM
LOOP SIZE: 182.000 m by 182.000 m
AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y)
TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 100.0000 N: 6.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 3.435 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			204.0	669.3	
1	87.99	41.17	162.8	534.1	0.467
2	16.87	61.05	101.7	333.6	3.61
3	748.3	202.1	-100.4	-329.4	0.270
4	2.74				

ALL PARAMETERS ARE FREE

CURRENT: 16.50 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 4 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	89008.8	85844.0	3.55
2	0.108	69488.7	68891.0	0.860
3	0.138	51786.9	52524.6	-1.42
4	0.175	37605.4	38992.2	-3.68
5	0.218	27587.7	28516.1	-3.36
6	0.278	18835.7	19238.3	-2.13
7	0.351	12526.6	12538.4	-0.0942
8	0.438	8073.6	7972.9	1.24
9	0.558	4792.4	4610.0	3.80
10	0.702	2674.5	2607.1	2.52
11	0.858	1545.9	1524.6	1.37
12	1.06	817.7	823.3	-0.683
13	1.37	377.0	388.9	-3.16

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	1.74	177.1	188.3	-6.28
15	2.17	94.31	97.93	-3.83

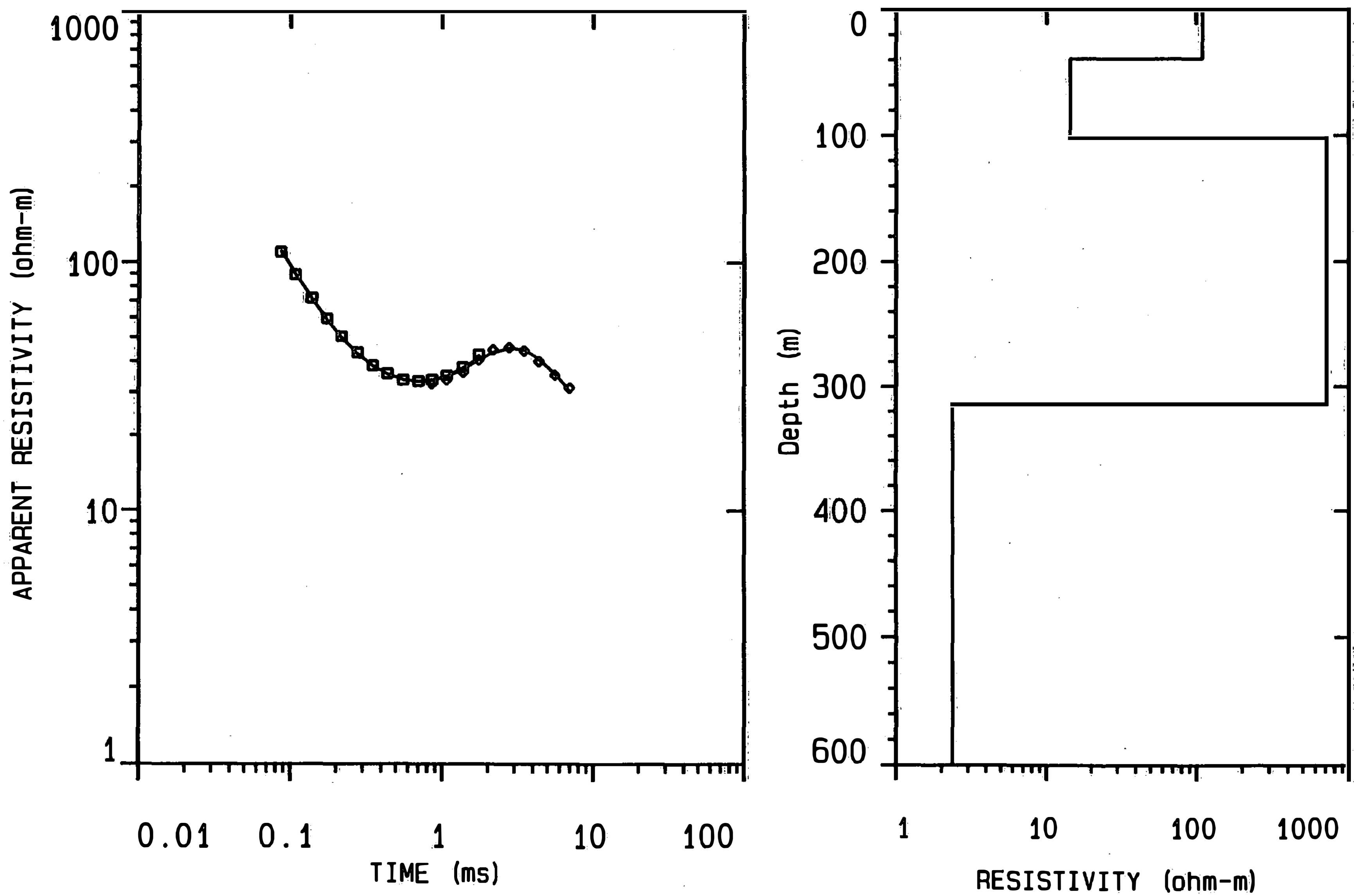
CURRENT: 16.50 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
16	0.857	1628.0	1539.8	5.41
17	1.06	861.5	833.2	3.27
18	1.37	403.9	398.5	1.34
19	1.74	191.6	197.3	-2.95
20	2.17	104.3	106.4	-1.99
21	2.77	60.43	58.84	2.61
22	3.50	38.63	36.55	5.38
23	4.37	26.39	25.36	3.89
24	5.56	17.74	17.73	0.0500
25	6.98	12.09	12.92	-6.88

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.25						
P 2	0.01	0.85					
P 3	0.00	0.00	0.00				
P 4	0.00	0.09	-0.01	0.26			
T 1	0.21	0.10	0.00	-0.06	0.85		
T 2	-0.09	-0.19	-0.03	0.16	0.16	0.73	
T 3	-0.01	0.02	0.01	-0.03	-0.01	0.02	0.99
	P 1	P 2	P 3	P 4	T 1	T 2	T 3

HOKU-7



APPARENT RESISTIVITY (ohm-m)
1000
100
10
1
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
600
1
10
100
1000
RESISTIVITY (ohm-m)

DATA SET: HOKU-7

CLIENT: PUU O HOKU RANCH
LOCATION: MOLOKAI, HAWAII
COUNTY: MAUI
PROJECT: PUU O HOKU RANCH
LOOP SIZE: 152.000 m by 152.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: E: 100.0000 N: 7.0000 SLOPE: NONE

DATE: 12-08-98
SOUNDING: 7
ELEVATION: 182.00 m
EQUIPMENT: Geonics PROTEM
AZIMUTH:
TIME CONSTANT: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 2.523 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			182.0	597.1	
1	110.0	39.20	142.7	468.2	0.356
2	14.42	62.78	80.00	262.5	4.35
3	720.0	212.1	-132.1	-433.4	0.294
4	2.37				

ALL PARAMETERS ARE FREE

CURRENT: 19.50 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 4 RAMP TIME: 105.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	88522.5	86641.3	2.12
2	0.108	69816.6	69277.4	0.772
3	0.138	52507.3	52687.7	-0.343
4	0.175	38491.0	39213.6	-1.87
5	0.218	28360.3	28845.6	-1.71
6	0.278	19418.7	19676.2	-1.32
7	0.351	12912.3	12997.9	-0.663
8	0.438	8328.0	8390.1	-0.746
9	0.558	4980.1	4946.0	0.684
10	0.702	2833.4	2851.2	-0.627
11	0.858	1685.3	1696.2	-0.646
12	1.06	925.5	930.2	-0.513
13	1.37	439.1	443.9	-1.10

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	1.74	202.5	212.8	-5.08

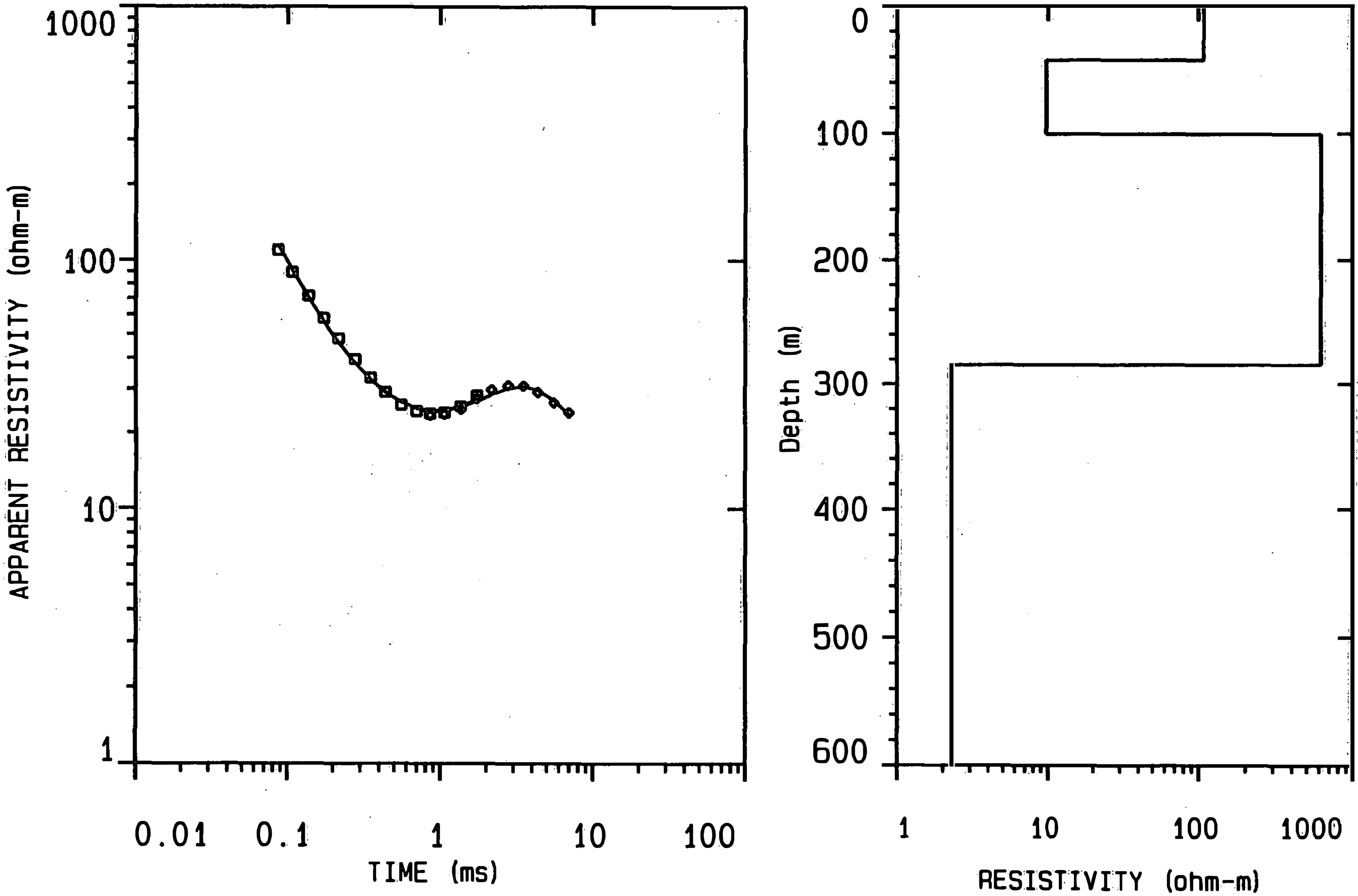
CURRENT: 19.50 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 105.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	0.857	1790.2	1709.8	4.49
16	1.06	981.2	938.3	4.37
17	1.37	471.2	451.7	4.14
18	1.74	218.1	220.1	-0.916
19	2.17	109.4	113.6	-3.80
20	2.77	57.43	58.09	-1.14
21	3.50	33.58	33.05	1.59
22	4.37	22.26	21.62	2.89
23	5.56	14.88	14.52	2.38
24	6.98	10.08	10.48	-3.96

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.07						
P 2	0.00	0.88					
P 3	0.00	-0.01	0.00				
P 4	0.00	0.07	-0.01	0.16			
T 1	0.16	0.08	0.00	-0.05	0.91		
T 2	-0.07	-0.16	-0.02	0.13	0.12	0.78	
T 3	-0.01	0.01	0.01	-0.03	-0.01	0.02	0.99
	P 1	P 2	P 3	P 4	T 1	T 2	T 3

HOKU-8


1000
100
10
1
APPARENT RESISTIVITY (ohm-m)
0.01
0.1
1
10
100
TIME (ms)
0
100
200
300
400
500
600
Depth (m)
1
10
100
1000
RESISTIVITY (ohm-m)

DATA SET: HOKU-8

CLIENT: PUU O HOKU RANCH
LOCATION: MOLOKAI, HAWAII
COUNTY: MAUI
PROJECT: PUU O HOKU RANCH
DATE: 12-08-98
SOUNDING: 8
ELEVATION: 182.00 m
EQUIPMENT: Geonics PROTEM
LOOP SIZE: 152.000 m by 152.000 m
AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y)
TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 100.0000 N: 8.0000
SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 4.129 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			182.0	597.1	
1	108.7	42.29	139.7	458.3	0.388
2	9.76	58.17	81.53	267.5	5.95
3	621.2	183.9	-102.4	-335.9	0.296
4	2.28				

ALL PARAMETERS ARE FREE

CURRENT: 19.50 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 3 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	88772.5	83013.5	6.48
2	0.108	69659.0	68168.7	2.13
3	0.138	52860.3	53833.1	-1.84
4	0.175	39758.1	41892.3	-5.36
5	0.218	30519.9	32371.0	-6.06
6	0.278	22290.0	23439.6	-5.15
7	0.351	16061.0	16485.6	-2.64
8	0.438	11269.7	11285.0	-0.135
9	0.558	7363.8	7097.8	3.61
10	0.702	4530.3	4349.4	3.99
11	0.858	2836.1	2722.2	4.01
12	1.06	1622.2	1575.6	2.87
13	1.37	794.2	795.4	-0.143

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	1.74	376.7	397.8	-5.61

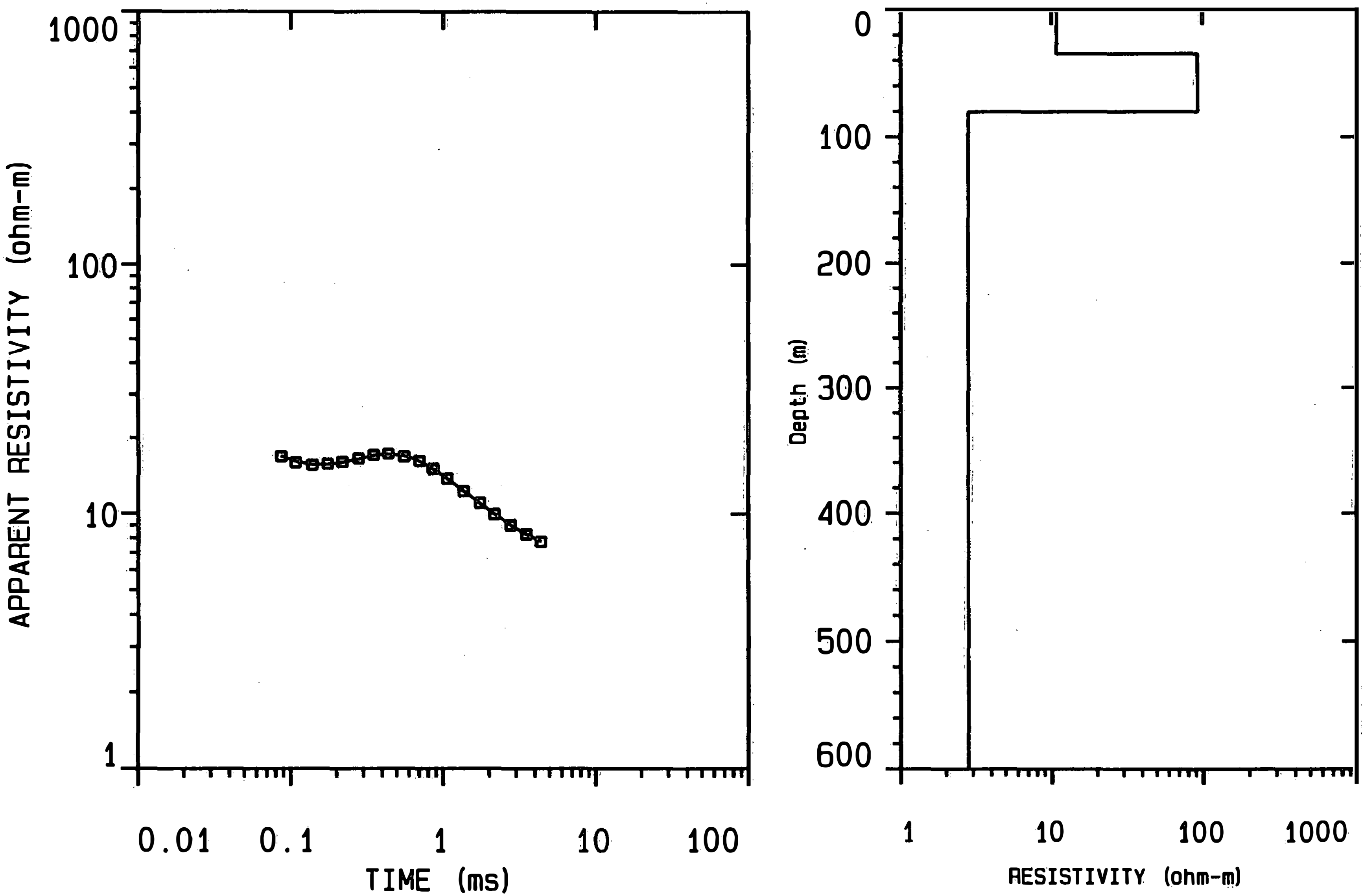
CURRENT: 19.50 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 6 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	0.857	2905.0	2741.4	5.63
16	1.06	1662.4	1586.7	4.55
17	1.37	828.0	806.0	2.65
18	1.74	393.4	407.9	-3.68
19	2.17	200.4	214.0	-6.74
20	2.77	102.2	106.5	-4.23
21	3.50	57.39	57.80	-0.718
22	4.37	36.02	34.87	3.19
23	5.56	22.75	22.06	3.05
24	6.98	14.80	15.12	-2.11

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	P 3	P 4	T 1	T 2	T 3
P 1	0.04						
P 2	-0.02	0.91					
P 3	0.00	0.00	0.00				
P 4	0.00	0.05	-0.01	0.13			
T 1	0.12	0.05	0.00	-0.03	0.95		
T 2	-0.07	-0.12	-0.02	0.10	0.07	0.83	
T 3	-0.01	0.00	0.01	-0.01	0.00	0.01	0.98

HOKU-9



APPARENT RESISTIVITY (ohm-m)
1000
100
10
1
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
600
1
10
100
1000
RESISTIVITY (ohm-m)

DATA SET: HOKU-9

CLIENT: PUU O HOKU RANCH
LOCATION: MOLOKAI, HAWAII
COUNTY: MAUI
PROJECT: PUU O HOKU RANCH
LOOP SIZE: 61.000 m by 61.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: E: 123.0000 N: 123.0000 SLOPE: NONE

DATE: 12-08-98
SOUNDING: 9
ELEVATION: 55.00 m
EQUIPMENT: Geonics PROTEM
AZIMUTH:
TIME CONSTANT: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 0.612 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			55.00	180.4	
1	10.74	34.72	20.27	66.5	3.23
2	92.96	45.68	-25.41	-83.4	0.491
3	2.81				

ALL PARAMETERS ARE FREE

CURRENT: 12.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 3 RAMP TIME: 40.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	146777.5	145504.1	0.867
2	0.108	91902.8	90727.9	1.27
3	0.138	51612.9	51248.2	0.706
4	0.175	28033.3	28286.6	-0.903
5	0.218	15765.7	15841.8	-0.483
6	0.278	8194.9	8233.7	-0.472
7	0.351	4360.9	4368.3	-0.169
8	0.438	2456.8	2464.3	-0.306
9	0.558	1393.9	1379.2	1.05
10	0.702	836.1	834.4	0.198
11	0.858	563.0	563.7	-0.115
12	1.06	374.3	373.6	0.189
13	1.37	237.9	238.1	-0.0644
14	1.74	153.5	154.2	-0.414

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	2.17	103.0	102.9	0.178
16	2.77	64.97	64.68	0.453
17	3.50	41.02	40.76	0.638
18	4.37	26.03	25.87	0.604

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	P 3	T 1	T 2
P 1	0.99				
P 2	0.00	0.01			
P 3	0.01	-0.01	0.93		
T 1	-0.02	-0.06	0.03	0.95	
T 2	0.01	0.07	0.01	0.02	0.98